2010-09

An analysis of Mobile Ad-Hoc Network performance to recommend a basis of issue for the U.S. Army Nett Warrior System

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http://hdl.handle.net/10945/5164

NAVAL POSTGRADUATE SCHOOL

MONTEREY, CALIFORNIA

THESIS

AN ANALYSIS OF MOBILE AD-HOC NETWORK PERFORMANCE TO RECOMMEND A BASIS OF ISSUE FOR THE U.S. ARMY NETT WARRIOR SYSTEM

by

W. Jacob Fry

September 2010

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REPORT DOCUMENTATION PAGE	*Form Approved OMB No. 0704-0188*

1. AGENCY USE ONLY ***(Leave blank)***	**2. REPORT DATE** September 2010	**3. REPORT TYPE AND DATES COVERED** Master's Thesis

4. TITLE AND SUBTITLE
An Analysis of Mobile Ad-Hoc Network Performance to Recommend a Basis of Issue for the U.S. Army Nett Warrior System

5. FUNDING NUMBERS

6. AUTHOR(S) W. Jacob Fry

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Naval Postgraduate School
Monterey, CA 93943-5000

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING /MONITORING AGENCY NAME(S) AND ADDRESS(ES)
U.S. Army Training and Doctrine Command Analysis Center
Monterey, CA 93943-5000

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES The views expressed in this thesis are those of the author and do not reflect the official policy or position of the Department of Defense or the U.S. Government. IRB Protocol number ___N/A___.

12a. DISTRIBUTION / AVAILABILITY STATEMENT
Approved for public release; distribution is unlimited

12b. DISTRIBUTION CODE
A

13. ABSTRACT (maximum 200 words)

The U.S. Army Nett Warrior System is a type of Mobile Ad-Hoc Network (MANET) designed to enhance situational awareness and communications within a U.S. Army Brigade Combat Team. It depends on reliable wireless communication provided by Enhanced Position Location Reporting System (EPLRS) Radio Sets. This study investigates the appropriate basis of issue for the fielding of these systems by examining how varying the number of fielded radios affects the system's ability to support Army communications requirements. In this thesis, we model network operations in three ways to evaluate the effects of varying the number of radios. The first model provides an idealized representation of network performance by calculating total throughput in the best case. The second model estimates the percentage of potential links that can be established simultaneously using a greedy heuristic and in a manner consistent with EPLRS design. The final model examines the ability of the network to support the distribution of situational awareness information using discrete event simulation to evaluate the percentage of successful transmissions for networks of varying radio densities. We exercise these models under various deployment scenarios and make recommendations regarding the fielding of these systems.

14. SUBJECT TERMS
EPLRS, Enhanced Position Location Reporting System, TIREM, Terrain Integrated Rough Earth Model, MANET, Mobile Ad-Hoc Network, Wireless Network Performance, Wireless Communication, SRRA, Simultaneous Routing and Resource Allocation

15. NUMBER OF PAGES
75

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	**18. SECURITY CLASSIFICATION OF THIS PAGE**	**19. SECURITY CLASSIFICATION OF ABSTRACT**	**20. LIMITATION OF ABSTRACT**
Unclassified	Unclassified	Unclassified	UU

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. 239-18

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Submitted in partial fulfillment of the
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MASTER OF SCIENCE IN OPERATIONS RESEARCH

from the

NAVAL POSTGRADUATE SCHOOL
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ABSTRACT

The U.S. Army Nett Warrior System is a type of Mobile Ad-Hoc Network (MANET) designed to enhance situational awareness and communications within a U.S. Army Brigade Combat Team. It depends on reliable wireless communication provided by Enhanced Position Location Reporting System (EPLRS) Radio Sets. This study investigates the appropriate basis of issue for the fielding of these systems by examining how varying the number of fielded radios affects the system's ability to support Army communications requirements. In this thesis, we model network operations in three ways to evaluate the effects of varying the number of radios. The first model provides an idealized representation of network performance by calculating total throughput in the best case. The second model estimates the percentage of potential links that can be established simultaneously using a greedy heuristic and in a manner consistent with EPLRS design. The final model examines the ability of the network to support the distribution of situational awareness information using discrete event simulation to evaluate the percentage of successful transmissions for networks of varying radio densities. We exercise these models under various deployment scenarios and make recommendations regarding the fielding of these systems.

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LIST OF ACRONYMS AND ABBREVIATIONS

ABCS	Army Battle Combat System
AP	Access Point
BCT	Brigade Combat Team
BOI	Basis of Issue
C2	Command and Control
CB	Citizens Band
CDMA	Code Division Multiple Access
CSMA	Carrier-Sense Multiple Access
CSMA-CA	Carrier Sense Multiple Access with Collision Avoidance
DAP	Dynamically Allocated PVC
DISA	Defense Information Systems Agency
ENM	EPLRS Network Manage
EPLRS	Enhanced Position Location Reporting System
FBCB2	Force Battle Command Brigade and Below
FDMA	Frequency Division Multiple Access
GPS	Global Positioning System
GSS	Ground Soldier System
HDR	High Data Rate
JCSS	Joint Communications Simulation System
LDR	Low Data Rate
LOS	Line of Sight
LTS	Logical Timeslot
MANET	Mobile Ad-Hoc Network
MSG	Multi-Source Group
NW	Nett Warrior
PLRS	Position Location Reporting System
PVC	Permanent Virtual Circuit
RS	Radio Set
RSS	Received Signal Strength
SEM	Spherical Earth Model

SINCGARS	Single Channel Ground and Airborne Radio System
SL	Squad Leader
SRRA	Simultaneous Routing and Resource Allocation
STK	Satellite Toolkit
TDMA	Time Division Multiple Access
TIREM	Terrain Integrated Rough Earth Model
TL	Team Leader
TRAC	TRADOC Analysis Center
TRADOC	Training and Doctrine Command
TSI	Timeslot Index
TU	Transmission Unit
UHF	Ultra High Frequency
USMC	United States Marine Corps
VoIP	Voice Over Internet Protocol
WMN	Wireless Mesh Network

EXECUTIVE SUMMARY

The modern battlefield is increasingly dependent on high-speed, high-capacity communications networks to help maintain situational awareness in complex operational environments. The U.S. Army Nett Warrior System (NW) is a type of Mobile Ad-Hoc Network (MANET) designed to enhance situational awareness and communications within a U.S. Army Brigade Combat Team (BCT). It depends on reliable wireless communication provided by Enhanced Position Location Reporting System (EPLRS) Radio Sets (RSs). This study investigates the appropriate Basis of Issue (BOI) for the fielding of these systems by examining how varying the number of radios fielded affects the system's ability to support Army communications requirements.

In this thesis, we model network operations in three ways to evaluate the effects of varying the number of radios (denoted here as *nodes*). The first model provides an idealized representation of network performance by calculating total throughput in the best case. We formulate a network flow problem that maximizes the utility of delivered traffic among all nodes in the network. Comparing the two BOI using this model reveals that total network throughput is greater with higher node density.

The next approach estimates the network's ability to support virtual private circuits called *needlines*. We determine a shortest path between sender and receiver in a manner consistent with EPLRS design and, using a greedy heuristic, determine the percentage of successful links that can be established simultaneously. This model provides insight into the ability of the different BOI to support point-to-point communications demands. We find that increasing the number of nodes provides more potential relays, which allows the network to operate at greater ranges.

The final model examines the ability of the network to distribute situational awareness information. Using discrete event simulation, we evaluate the percentage of successful transmissions, given a nominal transmit interval, for networks of varying radio

densities. The results indicate that while it is possible to increase the number of fielded radios to the point where performance degrades significantly, this occurs at much higher node densities than either BOI prescribes.

Based on the analysis of the three models presented, it is our finding that the deployment of additional radios does not have a significant detrimental effect on the ability of an EPLRS network to support data traffic. The issuance of more radios can improve the communications capabilities within a company under certain conditions. However, this study does not consider application specific usage or its impact on mission success. Those considerations could be the subject of future study.

ACKNOWLEDGMENTS

I would like to thank all of the faculty and staff of the Naval Postgraduate School Operations Research Department for providing me with the tools to see the world from a new perspective. I would especially like to acknowledge my thesis advisor, Dr. David Alderson, for all of his insight, patience, and support. Without his mentorship and guidance, this thesis would not have been possible. I would also like to thank Dr. Emily Craparo for her willingness to assist at a moment's notice, and her ability to always ask the "right" questions. Finally, I would like to thank my Lyndsay, who kept me fed, clothed, and happy during the countless hours spent at the computer.

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I. INTRODUCTION

A. PROBLEM DESCRIPTION

The modern battlefield is increasingly dependent on high-speed, high-capacity communications networks to help maintain situational awareness in complex operational environments. As new systems emerge, and old systems evolve, a unifying factor is the need to pass traffic effectively and efficiently across the network. However, as the operational space becomes inundated with new technologies, the overhead required to operate these systems becomes a greater concern to network designers and operators.

The U.S. Army Nett Warrior System (NW), formerly the Ground Soldier System (GSS), is a type of Mobile Ad-Hoc Network (MANET) designed to enhance situational awareness and communications within a U.S. Army Brigade Combat Team (BCT).

This study focuses on the Raytheon Corporation's Enhanced Position Location Reporting System (EPLRS) radio, currently in use by the U.S. Army, Navy, Marine Corps, and Air Force. EPLRS provides rapid, jam resistant, and secure data transfer to provide enhanced situational awareness and improved command and control (C2). Designed in the late 1980s, EPLRS was originally intended to deliver the geolocation functionality now provided by the Global Positioning System (GPS), allowing commanders to keep track of troop positions, but EPLRS has since been adapted for use in MANET applications. EPLRS provides a "digital backbone" for the tactical networks utilized by a host of C2 applications, including Force Battle Command Brigade and Below (FBCB2) and the Army Battle Command System (ABCS).

The Army relies on this system to provide valuable situational awareness and data transfer capabilities to its forces. Our goal is to determine how varying the number of radios fielded affects the system's ability to support Army communications requirements.

This study seeks to determine the appropriate Basis of Issue (BOI) for the fielding of these systems. The Army is considering two Bases of Issue for the deployment of EPLRS Radio Sets (RSs) to members of the BCT. In the "Squad Leader (SL) BOI," RSs are issued to leaders down to the SL level. Likewise, the "Team Leader (TL) BOI" issues

RSs down to the TL level. Our working definition is that this provides one RS to each Platoon Leader, Platoon Sergeant, SL and TL, where appropriate. Thus, there are 18 RSs in the SL BOI and 42 RSs in the TL BOI. We consider a Company-sized element consisting of three Platoons organized as illustrated in Figure 1.

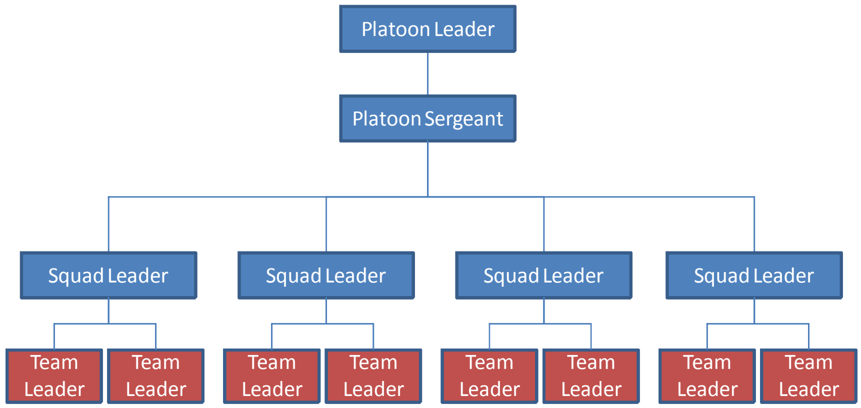

Figure 1. Platoon Organization Chart.

To inform our BOI recommendation, we evaluate EPLRS network performance by three different methods. We measure *total weighted throughput* by solving a max-flow problem to provide an idealized measure of how the network operates, we evaluate *point-to-point connectivity* based on the physics of wireless communications and its impact on network topology, and we measure the ability of different network topologies to maintain situational awareness information specific to EPLRS.

Intuitively, one expects that network connectivity improves with the number of radios, but there is more to performance than simple connectivity. This thesis explores several key tensions in the deployment of MANET systems. First, small changes in the quantity and geographic dispersion of wireless radios can have a big impact on the resulting network. In general, issuing more radios leads to greater connectivity. However, the deployment of additional radios also means greater competition for common network resources, which can actually reduce network performance as a whole. Understanding these tradeoffs is crucial for network designers and operators.

B. OBJECTIVES

This thesis seeks to identify the BOI that results in the best performing EPLRS network. We use a theoretical model of the physics of wireless communication, including terrain effects, traffic demand, and power constraints. By examining theoretical network performance over a variety of notional employment scenarios, we evaluate the ability of each BOI to support communications requirements. We use this information to recommend a BOI to the U.S. Army for EPLRS RSs as part of the NW system.

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II. BACKGROUND

A. ENHANCED POSITION LOCATION REPORTING SYSTEM

The U.S. Army began development of EPLRS as a follow-on program to the United States Marine Corps (USMC) Position Location Reporting System (PLRS) during the later stages of the Vietnam War. PLRS was originally intended to assist in the prevention of fratricide through better situational awareness of the battle space. Using PLRS as a starting point, the EPLRS program sought to add advanced communications capability to the existing PLRS role.

1. System Characteristics

Since its initial development, the EPLRS program has gone through several iterations, each one increasing the system's capabilities and reducing the required physical footprint. The version of EPLRS in use today consists of multiple RSs and at least one laptop running the EPLRS Network Manager (ENM) software, as shown in Figures 2 and 3.

Figure 2. EPLRS RS. (From Raytheon, 2008)

Figure 3. EPLRS ENM. (From MARCORSYSCOM, 2009)

EPLRS RSs operate using eight available channels in the Ultra High Frequency (UHF) band, between 420 and 450 MHz. They utilize spread spectrum, frequency-hopping waveforms to provide a robust, jam-resistant communications network. Each RS is capable of transmitting at 0.4, 3, 20, or 100 Watts, selectable by the user. A man-portable variant, the MicroLight-DM200, seen in Figure 4, is also available and capable of transmitting at 5 Watts utilizing the same EPLRS waveforms as the RSs.

Figure 4. MicroLight-DM200. (From Raytheon, 2009)

EPLRS networks employ several common techniques to allocate time and frequency resources. Time Division Multiple Access (TDMA) prevents traffic collisions within a single channel, Frequency Division Multiple Access (FDMA) segregates traffic among multiple channels, and Code Division Multiple Access (CDMA) utilizes frequency-hopping techniques to minimize effects of jamming. Each RS provides x.25, RS-232, and Ethernet interfaces to allow for wired connections to other network devices. An individual referred to as the EPLRS *Network Planner* is responsible for the planning and management of the deployed network.

2. Radio Resource Allocation

By providing discrete separations in time across the network, the TDMA protocol used by EPLRS enables uncontested communications within the network. Time is divided into a series of discrete *timeslots*. During each timeslot, only one RS can transmit while all others are waiting to receive. A *transmission unit (TU)* refers to the data transmitted or received in one timeslot. In order to coordinate this, each RS on the network has a clock that synchronizes with every other RS. Clock synchronization occurs when the ENM initializes the network.

Usage requirements determine *waveform* selection that, in turn, dictates *timeslot length*, either 2 ms or 4 ms. Once chosen, the timeslot remains fixed for the duration of the deployment. Table 1 provides a summary of the various waveform modes supported by EPLRS.

Waveform Group (Timeslot)	Waveform Mode	Data Rate (KBPS)	User Data Bits per Trans-mission	User Data Bytes per Trans-mission	General Anti-Jam Performance	90% Burst Throughput (dBm)	RS-to-RS Propagation Range (No Relays) (NMI)	RS-to-RS Propagation Range (No Relays) (Km)
Tactical Internet (2ms)	0	38	80	10	Better	-100	89	165
	1	38	80	10	Best	-102	68	126
	2	77	160	20	Better	-100	63	117
	3	115	240	30	Good	-98	62	115
	4	311	648	81	OK	-94	54	100
	14	430	896	112	OK	-94	15	28
Expanded Data (4ms)	5	65	272	34	Best	-102	91	169
	6	127	528	66	Better	-100	94	174
	7	184	768	96	Good	-98	85	157
	8	238	992	124	Good	-98	85	157
	9	486	2024	253	OK	-94	58	107

Table 1. EPLRS Waveform Modes. (From CECOM, 2005, p. 5–5)

a. Time Division

In a TDMA network, the largest time division is called an *epoch*. Each epoch contains 256 *frames*, with each frame containing 128 consecutive timeslots. Figure 5 provides an illustration of the time resource structure in an EPLRS network.

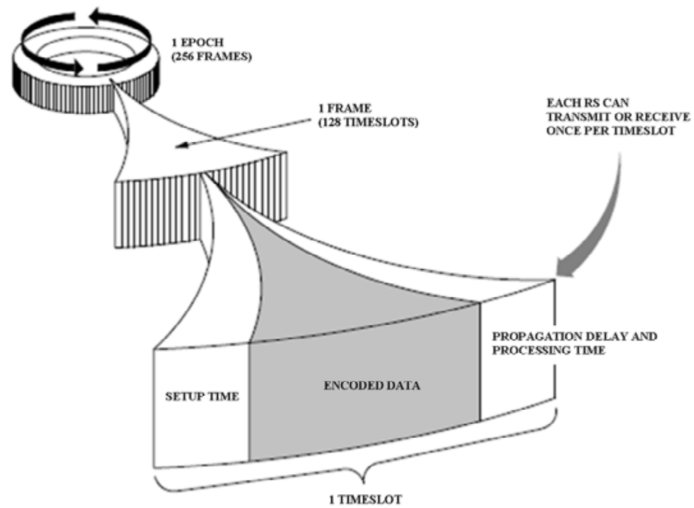

Figure 5. EPLRS Time Resource Structure. (CECOM, 2005, p. 2–2)

Referring to Table 2, each frame is divided into 16 vertical groups, each consisting of eight timeslots. The vertical groups are each labeled with their Timeslot Index (TSI) numbers 0–15 and the horizontal groups with their Logical Timeslot (LTS) numbers 0–7. The ENM uses these LTS divisions to assign time resources.

LTS 0	0	8	16	24	32	40	48	56	64	72	80	88	96	104	112	120
LTS 1	1	9	17	25	33	41	49	57	65	73	81	89	97	105	113	121
LTS 2	2	10	18	26	34	42	50	58	66	74	82	90	98	106	114	122
LTS 3	3	11	19	27	35	43	51	59	67	75	83	91	99	107	115	123
LTS 4	4	12	20	28	36	44	52	60	68	76	84	92	100	108	116	124
LTS 5	5	13	21	29	37	45	53	61	69	77	85	93	101	109	117	125
LTS 6	6	14	22	30	38	46	54	62	70	78	86	94	102	110	118	126
LTS 7	7	15	23	31	39	47	55	63	71	79	87	95	103	111	119	127
	TSI 0	TSI 1	TSI 2	TSI 3	TSI 4	TSI 5	TSI 6	TSI 7	TSI 8	TSI 9	TSI 10	TSI 11	TSI 12	TSI 13	TSI 14	TSI 15
	← 1 FRAME →															

Table 2. Timeslot Allocation in EPLRS Frame. (From CECOM, 2005, p. 2–3)

b. *Frequency Division*

EPLRS uses frequency division multiplexing across different *channels*, each corresponding to a different frequency, in order to minimize mutual interference and increase network capacity. EPLRS can use one of three different channel sets that define the maximum number of usable channels. After the Network Planner selects a channel set of five, six, or eight channels, he assigns each individual channel a frequency. Figure 6 illustrates the channel sets and their possible frequency options.

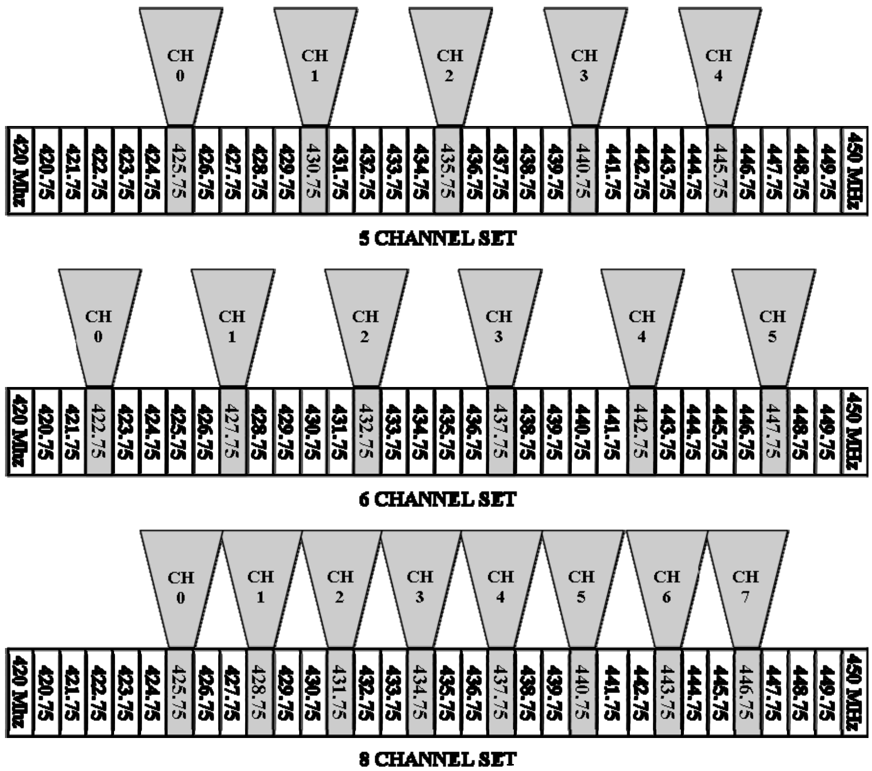

Figure 6. EPLRS Channel Options. (CECOM, 2005, p. 2–4)

Figure 7 illustrates an example of how the time and frequency resources described above can be allocated in an EPLRS network. The Network Planner assigns different types of traffic to each LTS prior to deployment of the system based on the communications requirements of the deploying forces.

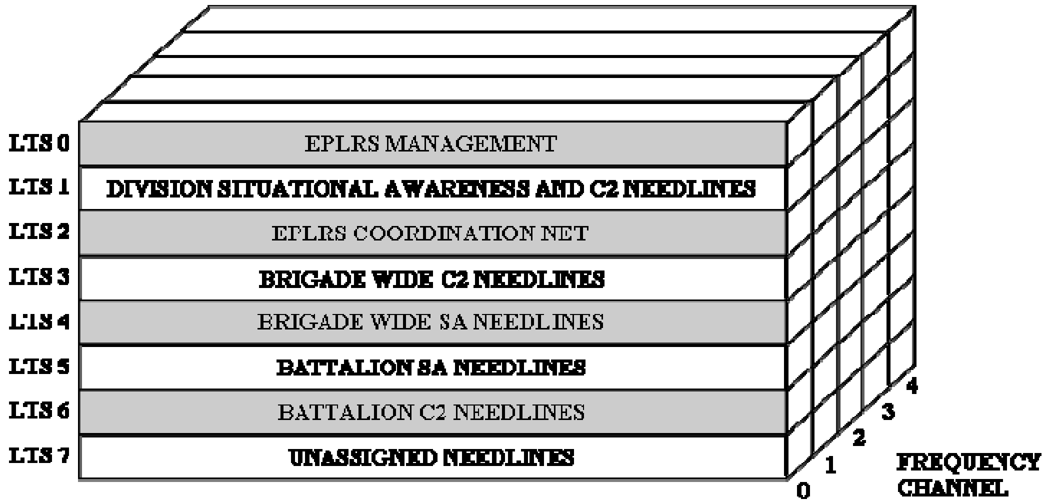

Figure 7. Example of EPLRS Resource Allocation. (CECOM, 2005, p. 2–8)

3. Needlines

The basic unit of end-to-end communication in an EPLRS network is a virtual circuit, known as a *needline*. Each needline is defined in terms of a type and waveform mode, timeslots, and frequency channels assigned to it. An individual designated as the Network Planner uses the ENM software to plan and initialize needlines. Selection of time and frequency resources directly affects needline capacity, while waveform choice varies the data rate, range, and error resiliency.

Each RS can support up to 32 needlines simultaneously; however, the maximum number is typically limited to 28 because of the timeslots used by the *coordination network*, a logical network that carries control traffic. The coordination network provides communication between the ENM node and the RSs, assisting in needline establishment and network performance monitoring.

EPLRS needlines fall into one of the following two categories. *Permanent Virtual Circuit* (PVC) needlines are pre-planned by the network manager and are available throughout the deployment period. Alternatively, *Dynamically Allocated PVC* (DAP) needlines are created when a need exists, and then are terminated when communications are complete. We discuss the four major types of needlines below.

a. Carrier-Sense Multiple Access (CSMA)

CSMA needlines allow users to broadcast data to a large number of recipients on demand, representing a many-to-many communications capability. "A CSMA needline operates like a group of people on a contention voice net, each speaking when he or she has something to say and when no one else is speaking" (Tharp, 2003). CSMA needlines primarily transfer situational awareness (i.e., unit positions) and C2 data, and these transmissions are not acknowledged. The EPLRS coordination network resides on a CSMA needline called *CSMA_DF*.

b. Multi-Source Group (MSG)

The MSG needline provides EPLRS users with a few-to-many communications capability. Messages are sent by a predefined set of source RSs to other RSs assigned to that needline, either directly or through designated relays. In the TDMA structure, timeslots are allocated for MSG needlines, resulting in less wasted bandwidth and guaranteed capacity without conflict. "An MSG needline operates like a group of people with bullhorns, each person talking in turn to many people who cannot talk back" (Tharp, 2003). MSG needlines are defined for one-way traffic such as movement orders or sensor data, and these transmissions are not acknowledged. We do not consider MSG needlines in this study.

c. Low Data Rate (LDR) Duplex

LDR duplex needlines establish a point-to-point communications path between two RSs, providing reliable data transfer with receipt acknowledgment at rates ranging from 20 bps to 16,192 bps. These needlines are automatically established by the coordination network using a path-finding algorithm that defines which RSs will function as relays to transfer data between the endpoints. Paths are re-negotiated as necessary to maintain the link. Time and frequency resources are reserved for duplex communications and are assigned to each duplex needline as required. LDR needlines are utilized for Voice over IP (VoIP) type communications.

d. High Data Rate (HDR) Duplex

HDR duplex needlines function much like the LDR version except the user data rates can be much higher, ranging from 600 bps to 121,440 bps. They allow for the transfer of data intensive messages such as full-motion video and large file transfers. Like the LDR duplex needlines, the coordination network automatically selects a path through the network by assigning specific relay nodes to establish the links that connect the endpoints. This process involves the assignment of frequency and time resources to each node in the needline to guarantee available bandwidth between the RSs.

B. LITERATURE REVIEW OF PREVIOUS WORK

The U.S. Army Training and Doctrine Command (TRADOC) Analysis Center (TRAC) Monterey initiated a study to examine the performance of the NW system as a function of EPLRS radio density (Evangelista, 2009). The results of this study use the probability of *line of sight* (LOS) between nodes and the message range probability, defined as the likelihood of successful traffic delivery as a function of range. The conclusions drawn from this study indicate that the TL BOI is the recommended employment strategy since it yields a more densely connected network. What this study does not consider, however, is how an increase in node density changes network performance.

Xiao et al. (2004) present a formulation for MANET design that maximizes the flow of traffic across a wireless network by optimally allocating communication resources. This Simultaneous Routing and Resource Allocation (SRRA) problem easily decomposes into two major sub-problems: network flow and communication resource allocation. We utilize a similar framework to calculate network performance within the constraints of our specific application.

Shankar (2008) utilizes the SRRA framework to determine optimal jammer placement in order to disrupt wireless network communications. He combines the SRRA definition of network flow with the attacker-defender techniques of Brown et al. (2006) to identify the maximum disruption of traffic flow.

Nicholas (2009) uses the SRRA formulation to identify the placement of wireless access points that maximizes a combination of signal coverage and network throughput. This application informs the design and deployment of wireless networks that rely on fixed access points to provide access to users in specific geographic regions. Nicholas (2009) achieves a high level of accuracy in the calculation of received signal strength using the standard link budget formula (Olexa, 2005) with the free space loss term determined by the Terrain-Integrated Rough-Earth Model (TIREM) of Alion Science & Technology Corporation (Alion, 2010).

Smith (2009) uses discrete event simulation to model the performance of three different wireless networking devices: EPLRS, the Single Channel Ground and Airborne Radio System (SINCGARS), and the Cooperative Diversity Radio. He examines average throughput and message completion rate as a measure of overall network performance. Smith (2009) uses a commercial simulation software suite known as the Joint Communications Simulation System (JCSS), maintained by the Defense Information Systems Agency (DISA). In his study, Smith (2009) fixes certain variables in an effort to aid comparison, but as a result, the simulated operation is not necessarily representative of how a properly planned and deployed system would function in a real-world scenario. The result is an underestimation of actual EPLRS network performance.

We seek to improve upon the collective analysis of EPLRS operation by modeling its use in the NW system. By representing system operation more accurately, we hope to gain greater insight into the effect of varying the network density to support a greater BOI.

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III. MODEL FORMULATION

A. WIRELESS COMMUNICATION LINKS

Wireless communication takes many forms, from simple systems dedicated to voice transmission like AM, FM, and Citizens Band (CB) radios, to more complex systems such as the 802.11x Wi-Fi and 802.16 Wi-Max networking standards. In each case, the principle is the same: transmission of information from one place to another without the restrictions of physical cables or wires.

Modeling wireless communications is inherently difficult due to a large number of variables that affect system performance. Understanding these variables is essential to accurately representing how these systems perform in real-world situations. The physics of wireless communications are relatively straightforward from a theoretical standpoint. There are well-established equations that describe how systems will perform. The difficulty in accurately representing real world vice theoretical performance is that conditions are constantly in flux and systems rarely behave according to the theoretical ideals. This study examines how the relative position of radios, transmit power, and other EPLRS-specific settings affect system performance, beginning with the most idealized conditions, and then adding layers of complexity to more accurately represent actual system performance.

1. Received Signal Strength

From a theoretical standpoint, the most important factor in the determination of wireless network performance is *received signal strength (RSS)*. In general, received signal strength is a function of transmitter power, distance between transmitter and receiver, and the interference and/or losses along the transmission path.

We calculate received signal strength ρ for an arc $(i, j) \in A$ according to the standard link budget formula (Olexa, 2005),

$$\rho_{ij} = P_{tx} + g_{tx} - L_{tx} - L_{fs} - L_m + g_{rx} - L_{rx}, \tag{3.1}$$

where P_{tx} is transmitted power in dBm, g_{tx} and g_{rx} are, respectively, the antenna gains of the transmitter and receiver in dBi, L_{tx} and L_{rx} are, respectively, the losses (i.e., from cables, connectors) of the transmitter and receiver in dB, L_{fs} is free-space path loss in dB, and L_m is miscellaneous loss (i.e., fade margin) in dB. In this generalization of the network, we assume nominal values for the antenna gains, transmitter and receiver losses, and miscellaneous losses, as shown in Table 3.

Transmitter Antenna Gain (g_{tx})	3 dBi
Receiver Antenna Gain (g_{rx})	3 dBi
Fade Margin (L_m)	30 dB
Transmitter Losses (L_{tx})	0 dBm
Receiver Losses (L_{rx})	0 dBm

Table 3. Received Signal Strength Calculation Assumptions.

Free-space path loss, L_{fs}, is the decrease in signal strength that results from the transmission of an electromagnetic wave along a line-of-sight path through free space. It can be determined using one of several methods.

One simple method for determining free-space path loss uses the inverse-square path loss model, as implemented by Xiao et al. (2004). Using this approach, the decrease in received signal strength is proportional to the inverse square of the distance between receiver and transmitter. The inverse-square path loss model represents the inverse of free-space path loss in Watts as

$$\frac{1}{L_{fs}} = \left(\frac{y_0}{y_{ij}}\right)^2 p_i, \tag{3.2}$$

where y_0 is some reference distance, y_{ij} is the distance between two radios i and j, and p_i is the transmission power at radio i in Watts. This method provides a simple, yet crude representation of path loss.

An alternative approach to determining free-space loss is a modification of the simple transmission formula presented by Friis (1946). This formulation uses not only the distance between the transmitter and receiver, but also the transmission frequency. The equation for free-space path loss is

$$L_{fs} = \left(\frac{4\pi \cdot Dist}{\lambda} \right)^2, \tag{3.3}$$

where λ is the signal wavelength in meters and *Dist* is the distance between transmitter and receiver in meters. Substituting into the previous equation,

$$\lambda = \frac{c}{f}, \tag{3.4}$$

where f is the frequency in hertz and c is the speed of light constant, yields

$$L_{fs} = \left(\frac{4\pi \cdot Dist \cdot f}{c} \right)^2, \tag{3.5}$$

which provides a value for free-space loss under ideal conditions.

Another method commonly employed for the determination of path loss is the Terrain-Integrated Rough-Earth Model (TIREM) of Alion Science & Technology Corporation (Alion, 2010). In addition to free-space losses, TIREM also accounts for losses due to atmospheric and ground effects. It also accounts for the curvature of the Earth, using the Spherical Earth Model (SEM) to determine if LOS exists between transmitter and receiver. Inputs to TIREM include the terrain profile between transmitter and receiver, information about the transmitter (antenna height, frequency, antenna polarization), the receiver (antenna height), atmospheric constants (surface refractivity, humidity), and ground constants (relative permittivity, conductivity). It provides very accurate estimates of path loss, but its major limitation is that it does not consider attenuation due to rain, foliage, or manmade obstacles. TIREM serves as the underlying path-loss model in many commercial simulation software platforms, including Analytical Graphics' Satellite Toolkit (STK) Suite and the Defense Information Systems Agency (DISA) Joint Communications Simulation System (JCSS).

In this thesis, we use TIREM to determine the path loss between transmitter and receiver. We assume nominal values for the TIREM inputs, shown in Table 4 and adapted from Nicholas (2009). We also assume a flat terrain profile, which results in an upper bound on actual received signal strengths.

Input Parameter	**Value**
Transmitter Frequency	450 MHz
Transmitter Antenna Height	2 m
Receiver Antenna Height	2 m
Antenna Polarization	Horizontal
Surface Refractivity	300 N-units
Humidity	5 g/m^3
Relative Permittivity of earth surface	25
Conductivity of earth surface	50 S/m

Table 4. TIREM Inputs

Although TIREM provides the most realistic representation of path loss, any of the models described above are valid methods to determine received signal strength. It is noteworthy that the qualitative results obtained using any of the path loss models are similar, and the only significant differences we see are in the scale of the calculated received signal strengths.

2. Link Capacity

In a wireless communications environment, several of factors affect link capacity. A theoretical upper bound on link capacity, measured in bits per second, comes from the classical Shannon Capacity Formula (Shannon, 1948), which states

$$\left(\text{Link Capacity}\right) \equiv b \log_2 \left(1 + \frac{Signal}{Noise}\right) \tag{3.6}$$

where b is the channel bandwidth in Hertz, and *Signal* and *Noise* are, respectively, the received signal strength and background noise in Watts.

The noise term in Equation (3.6) refers to the additive white Gaussian noise at each receiver. Noise at the receiver effectively reduces the received signal strength of the transmission. We represent background noise by

$$Noise = n_j \tag{3.7}$$

where nj is the background noise at radio j. We assume the value for background noise is −80 dBm (equivalent to 10-11 W).

Taking the antilog of Equation (3.1) and substituting into Equation (3.6) yields

$$\left(\text{Link Capacity}\right) = b\log_2\left(1+\frac{10^{\frac{g_{tx}+g_{rx}}{10}}}{n\left(10^{\frac{L_{fs}+L_m}{10}}\right)}p\right), \tag{3.8}$$

which we use to determine the theoretical capacity for each link in the network. This capacity represents the expected throughput, in bps, between a transmitter and receiver.

EPLRS radios can operate at four different power settings: 0.4 W, 3 W, 20 W, and 100 W. We evaluate the Shannon capacity for each of the four selectable power levels in EPLRS to obtain an upper bound on link capacities as a function of distance, as seen in Figure 8. This limit represents system performance under ideal conditions and does not account for limitations within EPLRS, which—in reality—result in lower observed throughput values.

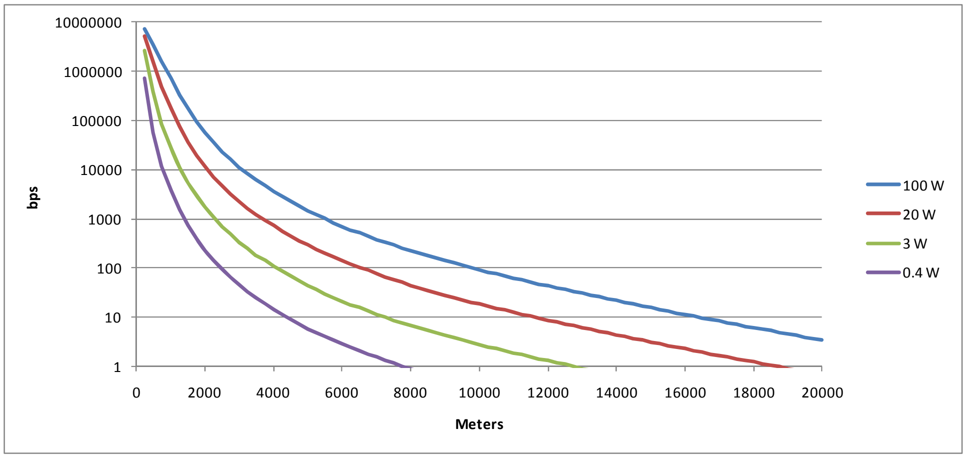

Figure 8. Calculated Shannon Link Capacities for EPLRS Power Settings.

In wireless communications, received signal strength dictates whether two nodes are able to establish and maintain a connection, which we define as the ability for one node to pass traffic to another. In order for a connection to exist, the received signal strength must exceed some minimum threshold. When it drops below the threshold, the connection is lost and the nodes are no longer able to exchange traffic directly. A decrease in received signal strength can be the result of varying any of the inputs to Equation (3.1). Increasing the distance between nodes, reducing transmitter power, or increasing background noise at the receiver all serve to reduce the received signal strength and eliminate connections between nodes.

B. WIRELESS NETWORKS

1. Background

There are several different types of wireless networks. Wireless mesh networks (WMNs), for example, rely on a system of access points (AP) to provide clients with the wireless coverage they require for connection to the network. In addition to the client–AP links, the APs connect to one another to form a high-capacity backbone that allows traffic to pass from users connected to one access point to users connected to another (Nicholas 2009, pp. 2–4).

Another type of wireless network, a MANET, consists of radios that connect to one another without dedicated APs. MANETs are self-organizing systems capable of forming networks of the fly, without the reliance on fixed APs. In a MANET, each client acts as an AP, providing a connection to the network for any other client within range. Table 5 details the primary differences between MANETs and WMNs.

Issue	***MANET***	***WMN***
Network Topology	Highly dynamic	Relatively static
Mobility of relay nodes	Medium to high	Low
Energy constraint	High	Low
Application characteristics	Temporary	Semi-permanent or permanent
Infrastructure requirement	Infrastructure less	Partial or full fixed
Relaying	Relaying by mobile nodes	Relaying by fixed nodes
Routing performance	Fully distributed on-demand routing preferred	Fully distributed or partially distributed with table-driven or hierarchical routing preferred
Deployment	Easy to deploy	Some planning required
Popular application scenario	Tactical communication	Tactical and civilian communication

Table 5. Differences Between WMN and MANET (From Zhang et al., 2007, p. 7).

One of the most important features of a MANET is its ability to self-organize. Dynamic routing protocols eliminate the necessity for any centralized network management. By removing the reliance on one node for managing traffic flow on the network, the flexibility of the network improves greatly, thus lending itself to providing the means for tactical communication in a military context.

Although EPLRS relies on the ENM node to initialize the network, it is able to continue normal operation without the ENM after the network is established. This means that EPLRS functions as a MANET and benefits from the flexibility its structure provides.

2. Network Behavior

When all nodes in the network are relatively close in distance to one another, the received signal strengths are all relatively high, and each node is capable of broadcasting

its traffic directly to the intended recipient without the need for signal relay by intermediate nodes. This occurs when the geographic distances between nodes are short, but also when transmitter powers are high, line of sight is clear, and background noise is minimal.

If conditions change, and received signal strength decreases, we see a shift in network behavior from a direct, point-to-point, broadcast regime to something that acts as a true network, requiring routing through relay nodes to facilitate traffic delivery, as illustrated in Figure 9.

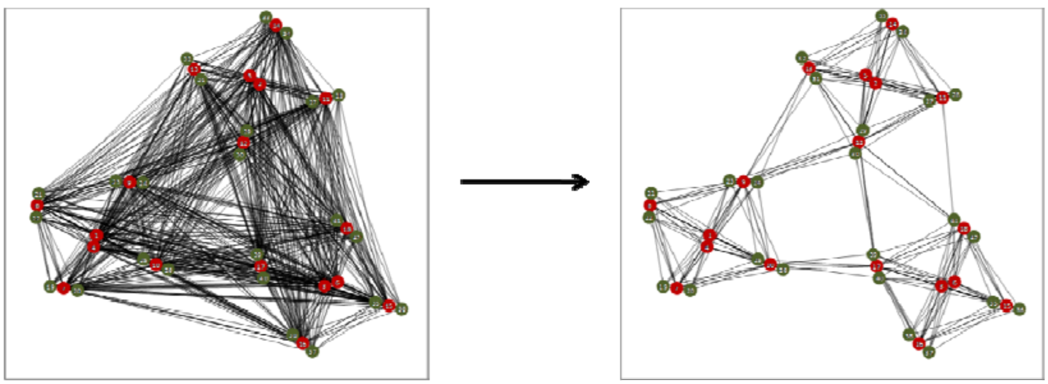

Figure 9. Effect of Reducing Received Signal Strength.

C. GEOGRAPHIC DISPERSION OF RADIOS

We introduce a model of the spatial *dispersion* of radios within the battle space. This dispersion model prescribes the relative locations of units, specifically the distances between them, which contribute to the connectivity between the nodes on the network. Other factors affecting connectivity are LOS and terrestrial and atmospheric effects.

We base the dispersion model in this thesis on a nominal geometric dispersion pattern consistent with previous EPLRS network density research (see Evangelista, 2009). We start by identifying the geographic center of the company. We then position three platoons some distance from this center point, referred to as the *platoon dispersion parameter*, with each platoon at 120º radial spacing. From each platoon point, we distribute four squads in a similar manner using 90º radial spacing and at a distance

defined by the *squad dispersion parameter*. Finally, we distribute two teams from the squad points using 180º radial spacing and a distance defined by the *team dispersion parameter*. We offset an additional node from the platoon point to represent a second command element at the platoon level. This dispersion pattern results in the placement of 42 nodes in the TL BOI, as compared to 18 nodes in the SL BOI, illustrated in Figures 10 and 11.

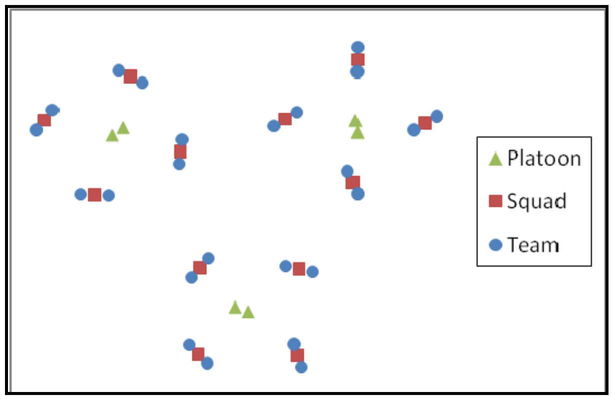

Figure 10. Example of TL BOI Node Dispersion.

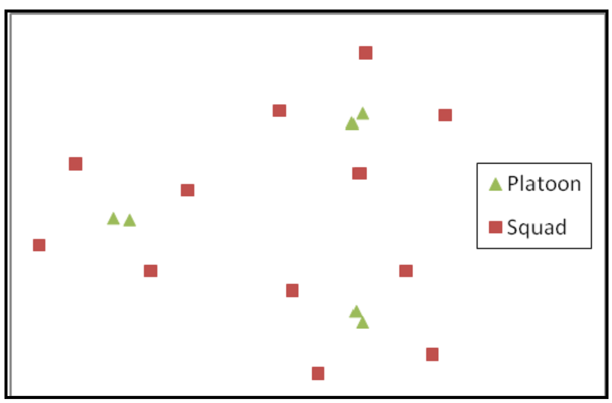

Figure 11. Example of SL BOI Node Dispersion.

To facilitate examination of the effects of varying distances between nodes, we introduce a *Dispersion Factor* that is a multiplied by the values in Table 6 to provide values for the platoon, squad, and team dispersion parameters described above.

Dispersion Parameter	*Multiplier*
Platoon	100 m
Squad	50 m
Team	20 m

Table 6. Dispersion Model Parameters.

Use of the Dispersion Factor allows for analysis across a variety of dispersion scenarios.

D. DEMAND FOR NETWORK TRAFFIC

1. CSMA Needlines

Demand for network resources depends almost entirely on the applications using the network. The remaining demand is comprised of the overhead required for the network to maintain itself. That overhead traffic travels over the coordination network. As mentioned earlier, the coordination network handles the configuration and monitoring of all RSs on the network. It gives the ENM the ability to administer remotely each RS while simultaneously handling requests for DAP needlines and determining traffic routing. Since every RS on the network is a member of the *CSMA_DF* needline, it follows that varying the number of nodes on the network could directly affect its performance.

Prior to deployment, the network planner selects several parameters that affect CSMA needline performance. For example, CSMA needlines can be set up to use different numbers of relays. Since EPLRS broadcasts traffic from one RS to any other RS within range, it must implement some method to prevent an infinite echo of messages within the network.

EPLRS accomplishes this using a user-defined parameter referred to as *Relay Coverage*. Relay Coverage establishes a maximum number of hops a TU may traverse on its way to its destination. Once the TU reaches the maximum number of hops, it is not retransmitted. The downside to this approach is that the RS transmitting the original

message must wait until each TU has reached its hop limit before sending the next TU. This ensures that different TUs of the same message are not being retransmitted through the network simultaneously. Having to wait some number of timeslots between transmissions effectively reduces the available throughput of a CSMA needline by a factor of *1/n,* where *n* is the Relay Coverage setting. This reduction in capacity can have a significant effect on network performance.

2. Duplex Needlines

Hosts requiring high-reliability two-way traffic rely on duplex needlines. For long-term communications requirements, PVC needlines are used. Since network managers plan these needlines prior to network deployment, the assignment of relays is fixed. For shorter-term communications where demand is emergent, DAP needlines are employed. Their dynamic nature makes them more appropriate for mobile units and their relay path-finding algorithm constantly monitors and updates relays as necessary. In addition, if a DAP needline is idle for a specified period, it is terminated in order to free up valuable network resources. As a result, PVC needlines are more appropriate for intermittent traffic between units.

Like CSMA needlines, both LDR and HDR Duplex Needlines are constrained by the Relay Coverage constraint, limiting the number of allowable relays to a maximum of five.

E. IDEALIZED SRRA MODEL

To determine a theoretical measure of network flow under ideal conditions, we use a modification of the SRRA formulation presented by Xiao et al. (2004) The goal is to maximize the utility of traffic flow across all nodes in the network.

In what follows, we define N to be a set of nodes, indexed by i (alias j, k, d). We represent directed arcs $(i, j) \in A$, where A is the set of all arcs satisfying the received

signal strength threshold. We define X_{ij}^{d} as the flow along arc (i, j) destined for node $d \in N$, and we define S_i^d as the total flow originating at node $i \in N$ and delivered to node $d \in N$.

1. Objective Function Definition

Following Xiao et al. (2004), we seek to maximize the total utility of all network traffic flow from source node *i* to sink node *d*. Nodes are able to act as both source and sink, as is the case in full duplex communications, or as either source or sink, as seen in half duplex transmissions. As in Nicholas (2009), total network utility is

$$\sum_{d} \sum_{i, i \neq d} \log_2 \left(S_i^d \right), \tag{3.9}$$

where S_i^d is the total flow from source node $i \in N$ to sink node $d \in D$. This formulation treats each unit of traffic equally, not distinguishing between traffic types or their relative importance.

In order to account for the different levels of importance of traffic passing through the network, we introduce terms w_i^d that allow us to differentiate end-to-end flows S_i^d. In what follows, we measure total network utility as

$$\sum_{d} \sum_{i, i \neq d} \log_2 \left(w_i^d + S_i^d \right), \tag{3.10}$$

where $w_i^d \in [0,1]$ is the term assigned to the traffic flow from source node $i \in N$ to sink node $d \in D$. When $w_i^d = 0$, we recover the original utility as in Equation (3.9). However, setting $w_i^d = 1$ effectively shifts the log utility function "to the left" resulting in a smaller penalty for flows that are near zero, shown in Figure 12. In practice, we set $w_i^d = 0$ for high priority traffic and $w_i^d = 1$ for low priority traffic.

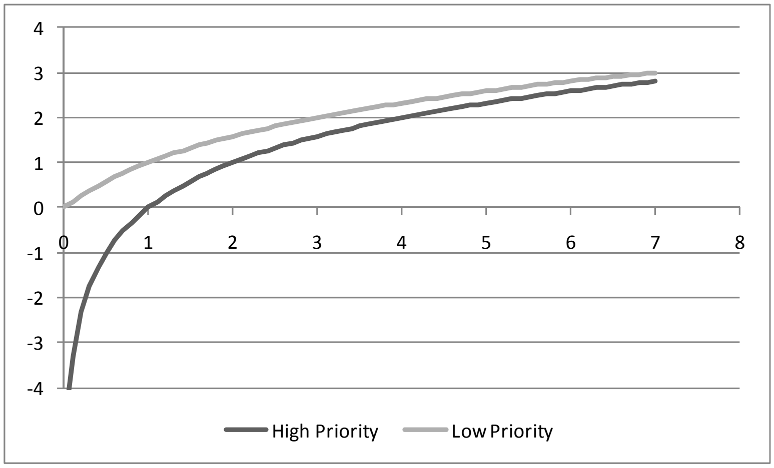

Figure 12. Effect of Weighting on Log Utility Function

2. Multicommodity Network Flow Problem

We represent data traffic across the network using a multicommodity network flow model, a practice consistent with network routing and optimization literature (Ahuja et al., 1993, pp. 690–691). Applied to the context of EPLRS communications networks, each node represents an EPLRS RS, and each arc represents the wireless link between two nodes. The commodities flowing through the network are the bits of data transmitted from one node to another. In a typical multicommodity network flow problem, link capacities are fixed, however, in the context of wireless networking, link capacities depend on available communications resources as described by Equation (3.8).

One defining characteristic of a network flow problem is the requirement for "balance of flow" at each node. We represent this in our formulation via a conservation of flow constraint

$$\sum_{k:(j,k)\in A} X_{jk}^{d} - \sum_{i:(i,j)\in A} X_{ij}^{d} = S_{j}^{d} \quad \forall j \in N, \forall d \in D, \tag{3.11}$$

where X_{ij}^{d} is the traffic flow along arc $(i,j) \in A$ to node $d \in D$, and S_{j}^{d} is the total flow of traffic from node $j \in N$ to node $d \in D$. Additionally, we require the total flow T_{ij} along an arc $(i,j) \in A$ to equal the sum of all traffic flows along that arc,

$$T_{ij} = \sum_{d} X_{ij}^{d} \quad \forall (i,j) \in A. \tag{3.12}$$

3. Link Capacity Constraint

The link capacity constraint takes into account the TDMA channel access method used by EPLRS RSs. Parameters of this constraint include the total available power and bandwidth for each source node as well as a time-slot fraction for each link. The assignment of a time-slot fraction to the link capacity constraint ensures the resulting capacity is consistent with a TDMA channel access scheme. Using Equation (3.8), the resulting constraint formulation is then

$$T_{ij} - F_{ij} b_i \log_2 \left(1 + \frac{10^{\frac{g_{tx}+g_{rx}}{10}}}{n_j \left(10^{\frac{L_{fs}+L_m}{10}} \right)} p_i \right) \leq 0 \quad \forall (i,j) \in A \tag{3.13}$$

where T_{ij} is the total flow along arc $(i,j) \in A$, and F_{ij} is the time-slot fraction of arc $(i,j) \in A$. We simplify Equation (3.13) by substituting

$$\rho_{ij} = \frac{10^{\frac{g_{tx}+g_{rx}}{10}}}{10^{\frac{L_{fs}+L_m}{10}}} p_i \tag{3.14}$$

which yields

$$T_{ij} - F_{ij} b_i \log_2 \left(1 + \frac{\rho_{ij}}{n_j} \right) \leq 0 \quad \forall (i,j) \in A \tag{3.15}$$

where ρ_{ij} is the received signal strength per arc $(i,j) \in A$.

Acceptable values for the time-slot fractions F_{ij} are further constrained to satisfy

$$\sum_{j:(i,j)\in A} F_{ij} \leq 1 \quad \forall i \in N \tag{3.16}$$

$$F_{ij} \geq 0 \quad \forall (i,j) \in A. \tag{3.17}$$

In our formulation, F_{ij} is a decision variable that selects optimal time-slot fractions for each link. This is in contrast to actual EPLRS logical time-slot selection,

which the network manager determines prior to deployment. Allowing the program to select optimal values for time-slot fraction represents an upper bound on the actual performance of the network.

4. EPLRS SRRA Formulation

Index Use

$i \in N$	node (*alias j,k,d)*
$(i, j) \in A$	directed arc

Calculated Data

ρ_{ij}	received signal strength per arc $(i, j) \in A$
b_i	maximum channel bandwidth per node $i \in N$
n_j	background noise per node $j \in N$
w_i^d	importance of traffic flow from node $i \in N$ destined for node $d \in N$

Decision Variables

S_i^d	total flow of traffic from node $i \in N$ destined for node $d \in N$
X_{ij}^d	traffic flow along arc $(i, j) \in A$ destined for node $d \in N$
T_{ij}	total flow along arc $(i, j) \in A$
F_{ij}	time-slot fraction of arc $(i, j) \in A$

Formulation

$$\max_{S,X,T,F} \sum_{d} \sum_{i:i \neq d} \log_2 \left(w_i^d + S_i^d \right)$$

$$s.t. \quad \sum_{k:(j,k) \in A} X_{jk}^d - \sum_{i:(i,j) \in A} X_{ij}^d = S_j^d \qquad \forall j \in N, \forall d \in D$$

$$T_{ij} = \sum_{d} X_{ij}^d \qquad \forall (i, j) \in A$$

$$T_{ij} - F_{ij} b_i \log_2 \left(1 + \frac{\rho_{ij}}{n_j} \right) \leq 0 \qquad \forall (i, j) \in A$$

$$\sum_{i:(i,j) \in A} F_{ij} \leq 1 \qquad \forall i \in N$$

$$S_i^d \geq 0 \qquad i, d \in N, \; i \neq d$$

$$X_{ij}^d \geq 0 \qquad \forall (i, j) \in A, \; \forall d \in D$$

$$T_{ij} \geq 0 \qquad \forall (i, j) \in A$$

$$F_{ij} \geq 0 \qquad \forall (i, j) \in A$$

5. Total Network Throughput

Given an optimal solution to this problem, we can calculate the total network throughput, evaluated by:

$$\text{Total Throughput} = \sum_{i}\sum_{d} S_i^d \quad \forall i \in N, \forall d \in D\,. \tag{3.18}$$

This approach provides an upper bound on network performance based on the physics of wireless communication under ideal operating conditions (i.e., perfect LOS, uniform background noise).

F. STATIC POINT-TO-POINT TRAFFIC MODEL

To understand how changes in the number of nodes affects the ability of units to communicate on the network using point-to-point methods (LDR or HDR duplex needlines), we present a model of static traffic demand. This model considers a point-to-point link between every pair of nodes and evaluates whether or not the link can exist.

1. Relay Path-Finding

As in an EPLRS network, we use a relay path-finding algorithm to determine the route traffic will take through the network. This path is constrained by a Relay Coverage setting of five, and we restrict the maximum number of needlines each RS can support is fixed at 32. We use an implementation of Dijkstra’s algorithm to find the shortest path, with regards to Euclidean distance, through the network while obeying the aforementioned constraints (Ahuja et al., 1993, p. 109). The relay-path finding algorithm used by EPLRS is proprietary; however, our approach mimics its performance.

2. Demand Definition

Using a static representation of the network, we assess how many point-to-point links are possible while operating within the confines of the relay coverage and needline constraints. To determine this, we first define a list of end-to-end traffic priorities. We base these priorities on the relative importance of each node within the network when placed into the context of an infantry company. Nodes representing higher echelons of the command structure have priority over lower ranking nodes. The result is an all-pairs

list broken into three subgroups: links between two high importance nodes, links between a high importance node and a low importance node, and links between two low importance nodes, as shown in Table 7.

Priority	Group Make-Up
1	High ↔ High
2	High ↔ Low
3	Low ↔ Low

Table 7. Point-to-Point Priorities.

We designate Platoon Leaders, Platoon Sergeants, and Squad Leaders as high importance nodes and Team Leaders as low importance nodes. The result is a list of 1722 point-to-point links in the TL BOI and 306 links in the SL BOI.

3. Received Signal Strength Threshold

As discussed in Section II.B.2, a threshold on received signal strength determines whether a link exists. If the received signal strength drops below the system threshold, the connection is no longer possible. Based on the average of the published *90% Burst Throughput* levels for EPLRS waveforms (Table 1), we assume this threshold to be –98 dBm for this study. Using the values from Table 3, we calculate the received signal strength between every node in the network, and we assume that only links whose value is greater than the threshold are present.

4. Methodology

In the static point-to-point model, we are concerned with the number of requests the network is able to satisfy. We generate a list of all node pairs and then randomize each priority subgroup to ensure uniform distribution within the subgroup. This results in a random all pairs list grouped by priority. A simplified explanation is shown in Figure 13.

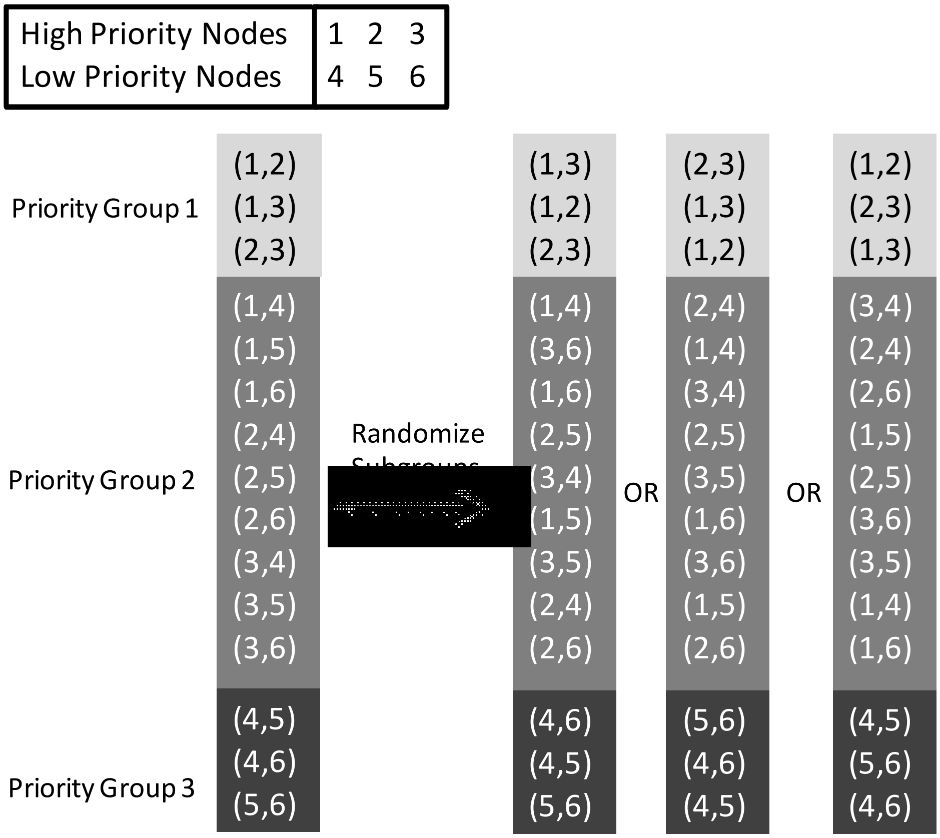

Figure 13. Example of Demand List Construction. We randomize the order of each origin-destination pair within each subgroup.

Using this list, we add point-to-point connections one at a time. The relay path-finding algorithm determines the shortest path between each source-destination pair. If a path connects the pair while satisfying the relay coverage and needline constraints, the link is a success. If not, the link is a failure. We attempt each connection in the list in turn. This greedy algorithm allows us to approximate the percentage of total connections possible given the constraints provided.

This static model provides insight into the effects of adding additional nodes to the network. Their addition, while potentially increasing the traffic demand on the network, also provides more relays to aid in satisfying point-to-point connections. If the traffic demand of the additional nodes is relatively low, then their inclusion in the network only serves to enhance the performance of the network in terms of duplex needline connections.

G. POSITION UPDATE MESSAGE MODEL

As previously described, CSMA needlines are used primarily to pass location information to enhance the situational awareness of the command element and to prevent fratricide. RSs periodically transmit position-update messages that are collected by the ENM and then broadcast over the network, providing each user with a common operating picture of the battle space. The periodicity of these messages is based on the node type and is a function of both time and movement.

Nodes transmit position-update messages according to user defined time and motion filters. Time and distance intervals are node-specific to account for relative speeds of units and frequency of changes in position, shown in Table 8.

Node Type	Time Filter	Motion Filter
Auxiliary ground unit	1–600 seconds	10–400 meters
Manpack unit	1–600 seconds	10–100 meters
Surface vehicle	1–500 seconds	50–200 meters
Airborne rotary-wing unit	1–64 seconds	100–2000 meters
Airborne fixed-wing unit	1–64 seconds	100–2000 meters

Table 8. EPLRS Position Update Filters. (From CECOM, 2005, pp. 8-16–8-17)

Intuitively, one expects that increasing the number of RSs increases the number of position-update messages transmitted across the network. The tension in this problem lies in determining how many RSs it takes to degrade significantly the position reporting functionality of EPLRS.

1. Carrier Sense Multiple Access With Collision Avoidance (CSMA-CA)

In addition to the Relay Coverage constraints imposed by EPLRS on CSMA needlines, there is another important factor to consider. In order for all nodes to share frequency resources, EPLRS implements a CSMA-CA multiple access method. Given

the discrete nature of timeslots in a TDMA system, CSMA-CA acts to reduce traffic collisions that occur when two RSs attempt to transmit in the same timeslot.

The basic idea of CSMA-CA is that each RS on the network "listens" to the channel when it is not transmitting. Before the RS attempts to transmit, it determines whether the channel is already in use by another RS or if it is idle. If the RS senses the channel is idle, it will begin transmitting in the next timeslot assigned to the needline. If the channel is busy, the RS will wait a random number of timeslots before attempting to transmit again. The random "back off times" help to reduce the number of collisions that occur when there are multiple RSs waiting to transmit. If every RS attempted to transmit in the first available idle timeslot, collisions would be much more likely to occur.

2. Simulation Model

The discrete nature of the EPLRS TDMA implementation, shown in Table 2, lends itself to a simulation approach to understanding how many RSs it takes to overwhelm the system. Varying the time intervals between position-update messages allows us to measure the likelihood of successful message transmission.

The discrete event simulation replicates CSMA-CA behavior by scheduling position-update messages at specified intervals and then attempting to "send" them in their scheduled time step. We assume each time step is long enough for the message to traverse the network up to the Relay Coverage limit. If the needline is idle when a scheduled transmission comes up, the state of the needline becomes busy and we record a successful transmission. If the state is busy, we insert a randomly generated delay and, following that delay, the transmission is attempted again.

Evaluating the number of successes versus the number of attempts allows us to determine a probability of successfully sending a message as a function of the number of nodes and the interval between transmission attempts. Maintaining a high level of situational awareness depends on the successful receipt of timely position updates. If the transmit interval is too long or the number of nodes too large, the ability of the system to provide that situational awareness is decreased.

IV. ANALYSIS

A. IDEALIZED SRRA MODEL

We examine network performance by solving our SRRA formulation from Section III.E.4. and evaluating the total throughput (Equation 3.18) across a range of dispersion factors. We perform this experiment on two possible transmit power scenarios.

1. Homogeneous Deployment

The first scenario is a homogenous distribution of 5 W radios, illustrated in Figure 14.

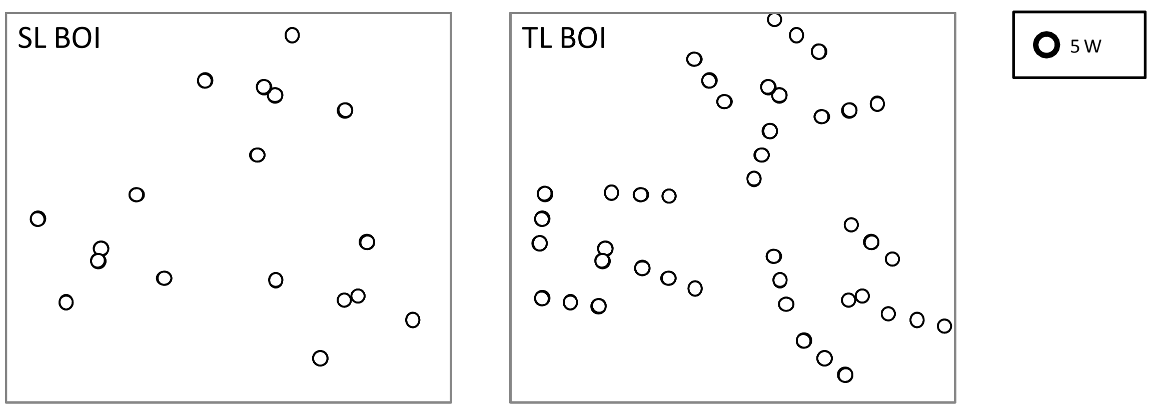

Figure 14. Network Topologies—Homogeneous (5 W).

We start with a dispersion factor of one, meaning that nodes are spaced according to Table 6. In this case, radios are so close that the network is completely connected and every node is capable of connecting to any other node directly. We then increase the dispersion factor, which "stretches" the nodes apart. As this happens, the received signal strength of each link decreases. When the received signal strength of a link reaches the −98 dBm threshold, connectivity between nodes is lost, resulting in a decrease in the number of links, shown in Figure 15.

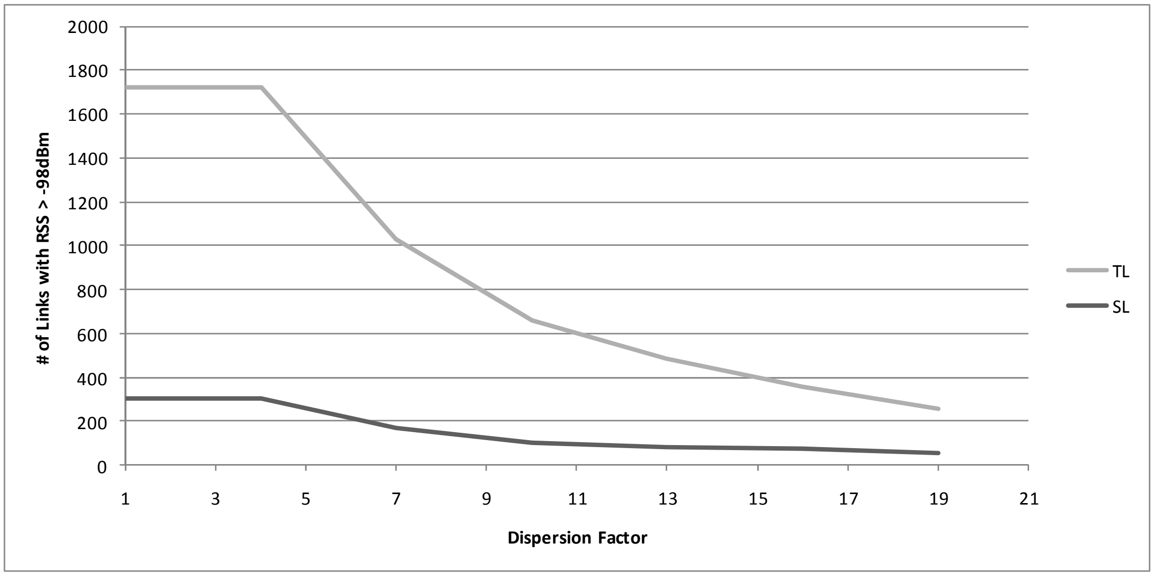

Figure 15. Number of Links—Homogenous (5 W). TL BOI provides a much greater number of links, but many are low priority.

Eventually, the decreasing signal strength causes platoons to lose connectivity altogether, as seen in Figure 16.

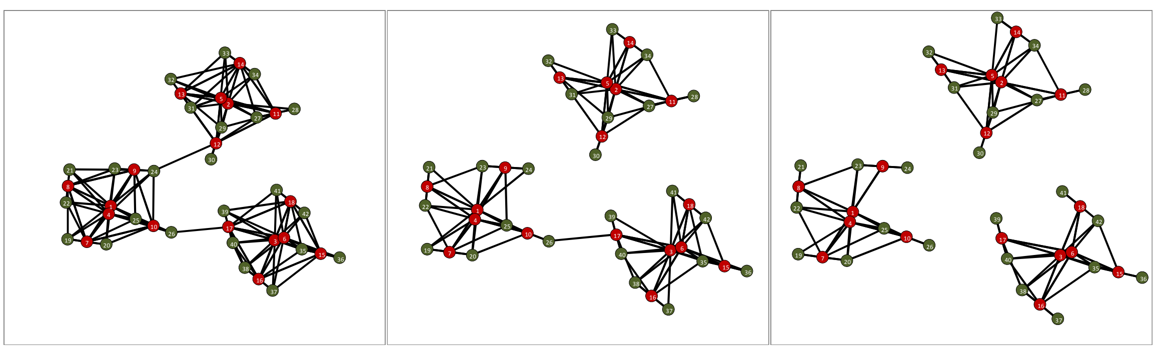

Figure 16. Loss of Platoon Connectivity.

We calculate the total network throughput by Equation (3.18) across a range of dispersion factors to determine a measure of network performance. With all radios set to the same power, the total network throughput is higher for the TL BOI across all dispersion factors, shown in Figure 17.

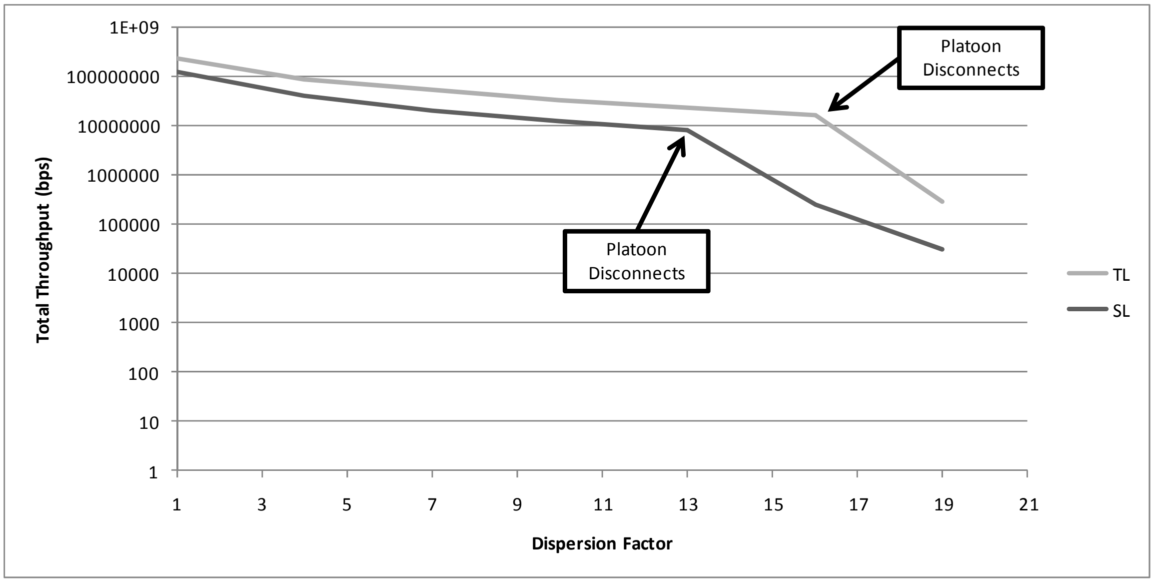

Figure 17. Total Throughput—Homogenous (5 W).

This behavior is intuitive in that one would expect to see a higher total throughput with more nodes simply due to the significantly higher number of links. As the dispersion factor increases, and received signal strength decreases, we see a decline in total throughput. The sudden drops in total throughput occur when one platoon loses connectivity with another. This happens for both the SL BOI and the TL BOI, but at different dispersion factors.

The higher total throughput values for the TL BOI are the result of the TL nodes acting to relay traffic back to their respective platoons, maintaining inter-platoon connectivity at greater ranges.

2. Heterogeneous Deployment

In the second scenario, we explore the effects of a heterogeneous deployment of RSs. We assume that the Platoon Leaders, Platoon Sergeants, and Squad Leaders have 100 W radios and the Team Leaders have 5 W radios. The resulting network topologies are shown in Figure 18.

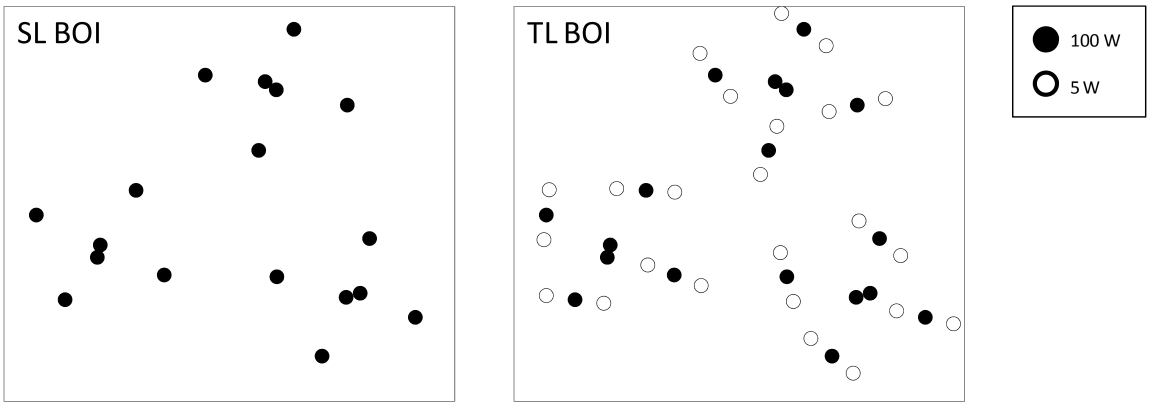

Figure 18. Network Topologies—Heterogeneous (100W, 5W).

An obvious benefit of the high power setting is that connectivity is maintained at much higher dispersion factor values, resulting in a greater number of links at greater distances, shown in Figure 19. However, operation of the system at high transmit powers increases the risk of jamming, electronic countermeasures, and signal interception.

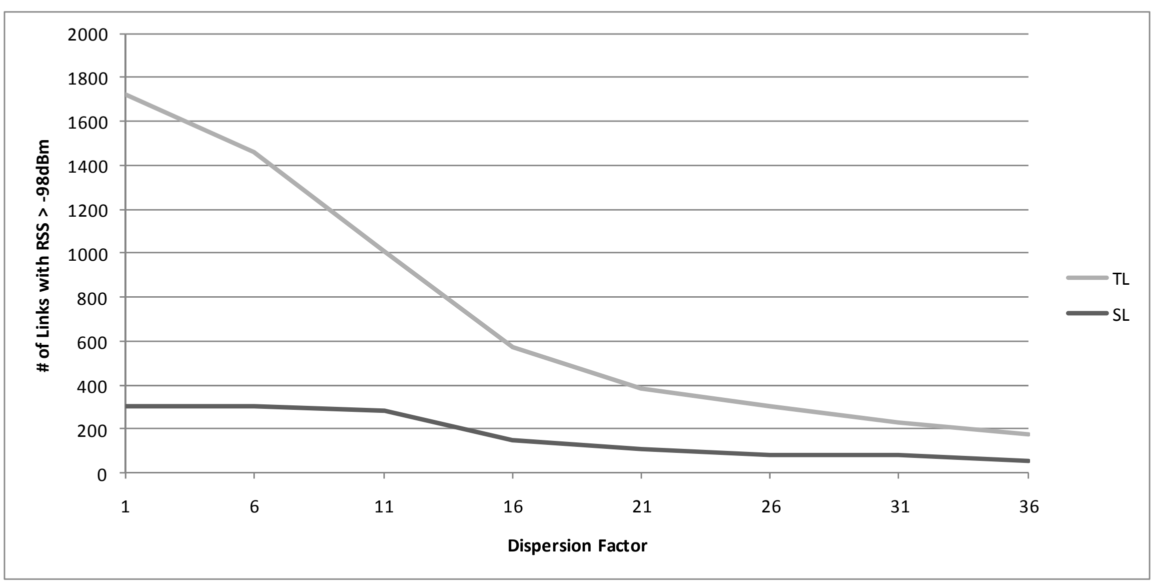

Figure 19. Number of Links—Heterogeneous (100W, 5W).

Total throughput values, shown in Figure 20, demonstrate that the increase in the number of nodes in the TL BOI does not have a significant effect on network performance despite the greater number of links.

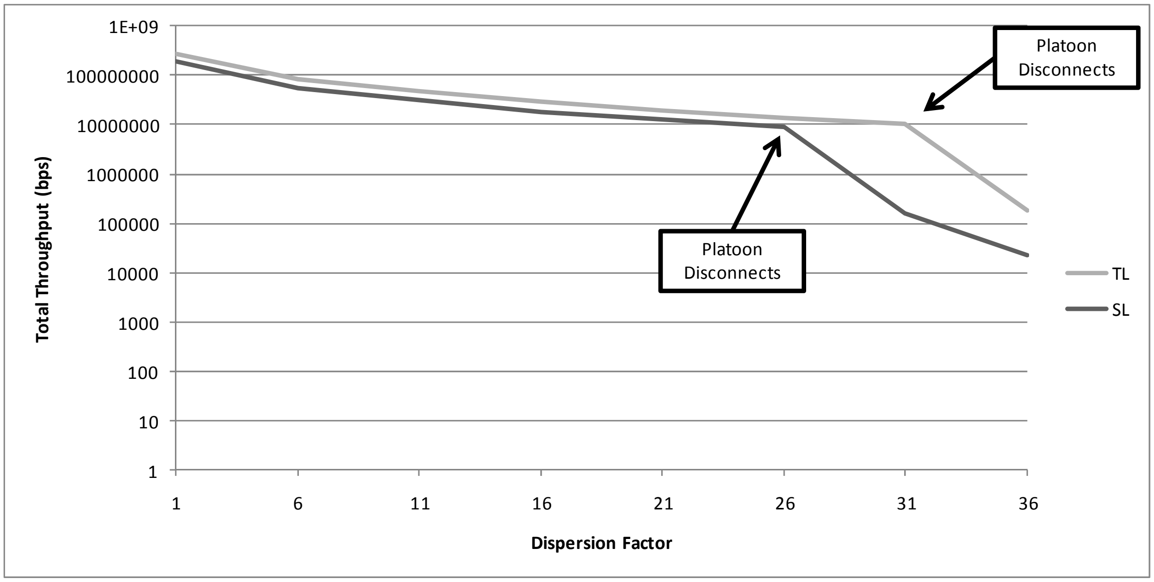

Figure 20. Total Throughput—Heterogeneous (100W, 5W).

The similarities in total throughput between bases of issue, shown in Figure 20, indicate that the benefits from peripheral nodes acting as relays are less noteworthy when high-power links dominate inter-platoon connectivity.

The results of the Idealized SRRA Model indicate that increasing the number of nodes, as seen in the TL BOI, does not have any detrimental effects on total network throughput and, in some dispersion scenarios, serves to increase the total network throughput by providing relays to maintain connectivity between distant nodes.

B. STATIC POINT-TO-POINT MODEL

The Point-To-Point model evaluates needline supportability within the constraints provided by the physics of wireless communications and EPLRS design characteristics.

1. Homogeneous Deployment

First, we examine the ability of a homogenous network (all 5 W radios) to support connections without Relay Coverage or needline constraints (No Restrictions) to illustrate how many hops it takes to satisfy all point-to-point demands. Figure 21 shows the percentage of connections between origin-destination (O-D) pairs that are possible by number of hops, across a range of dispersion factors for the SL BOI.

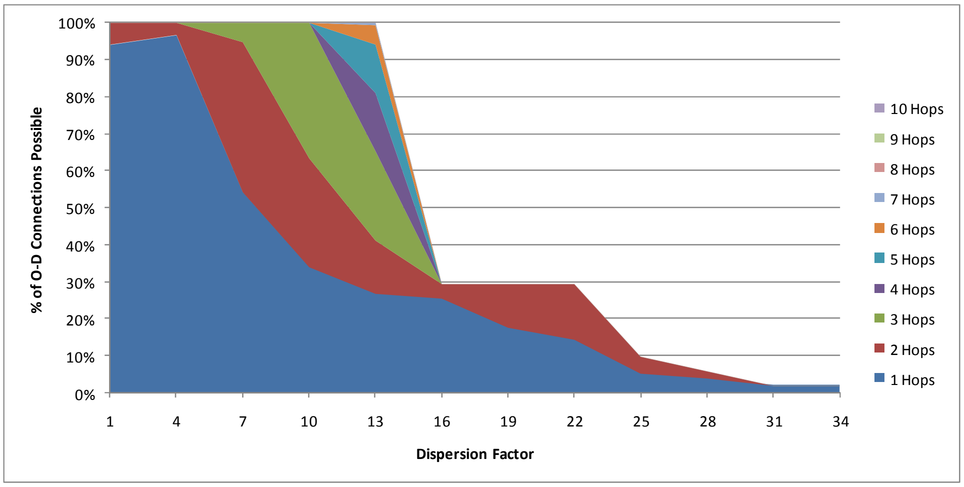

Figure 21. Percent of Point-To-Point Connections, No Restrictions (Homogeneous, 5W, SL BOI). Most connections use 1–3 hops.

We see that 100% of origin-destination connections are possible until the platoons become disconnected, as shown in Figure 16, and that no origin-destination pair uses more than seven hops. Figure 22 shows that in the TL BOI, the network is able to support 100% of the connections to higher dispersion factors due to the presence of more radios acting as relays. We see that as the dispersion factor increases, more hops are required to maintain 100% connectivity.

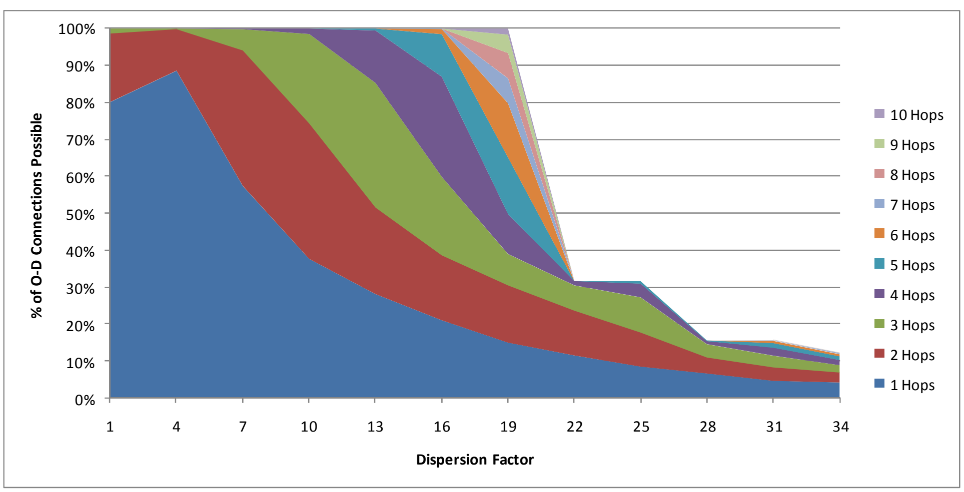

Figure 22. Percent of Point-To-Point Connections, No Restrictions (Homogenous, 5W, TL BOI). Greater number of 4–10 hop connections.

Comparison of the two bases of issue in a homogenous deployment scenario highlights the increased connectivity that results from the issue of a greater number of radios.

2. Heterogeneous Deployment

Figures 23 and 24 show the results of the same study, only we now consider a heterogeneous network that issues 5 W radios to the Team Leaders and 100 W radios to everyone else.

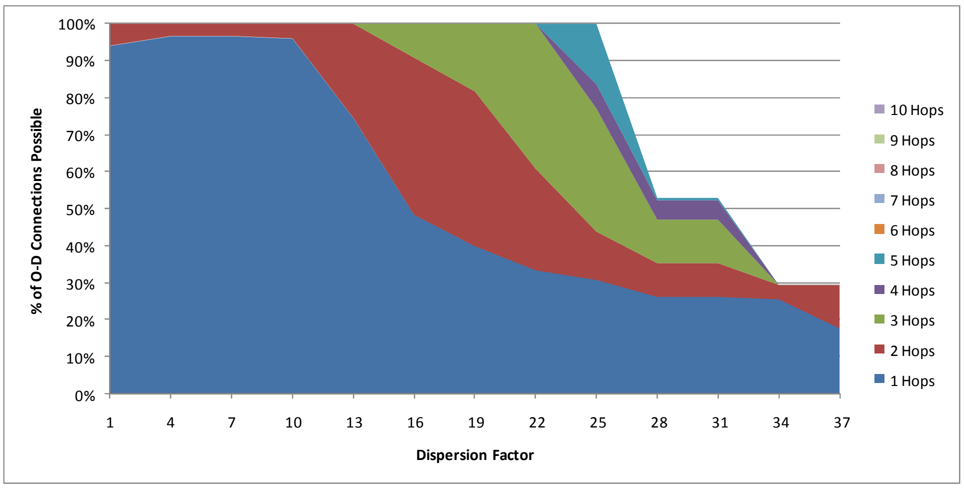

Figure 23. Percent of Point-To-Point Connections, No Restrictions (Heterogeneous, 100W–5W, SL BOI).

Intuitively, deployment of the 100 W radios increases the distance, as measured in dispersion factor, to which 100% connectivity can be maintained. Since the SL BOI does not issue radios to the Team Leaders, Figure 23 represents the equivalent homogenous network with 100 W radios.

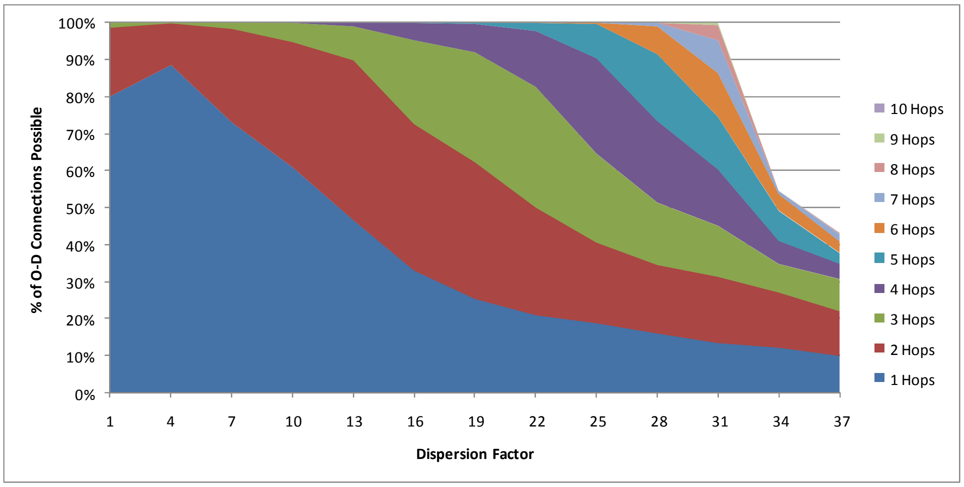

Figure 24. Percent of Point-To-Point Connections, No Restrictions (Heterogeneous, 100W–5W, TL BOI).

A comparison of Figures 23 and 24 reveals that the introduction of additional 5 W radios enhances the network's overall connectivity at greater dispersion factors. The benefits of additional radios acting as relays, seen in the homogenous deployment scenario, are also observed in the heterogeneous case. Evidence of this is the greater number of links of four hops and greater.

3. EPLRS Constraints

While examination of the total possible numbers of connections is insightful, it does not consider any of the additional constraints imposed by EPLRS itself; namely the Relay Coverage setting and the needline constraint. As mentioned previously, EPLRS LDR and HDR duplex needlines support a maximum Relay Coverage setting of five hops and no RS can support more than 32 needlines simultaneously.

Here we examine the effects of these constraints using a greedy heuristic that attempts to connect each origin-destination pair simultaneously. We recognize that this situation may not arise in normal system operation, but include it as it represents the greatest demand scenario. The methodology for ordering the connection attempts is based on priority and is described in Section III.F.4. Two possible results of this heuristic approach are shown in Figure 25.

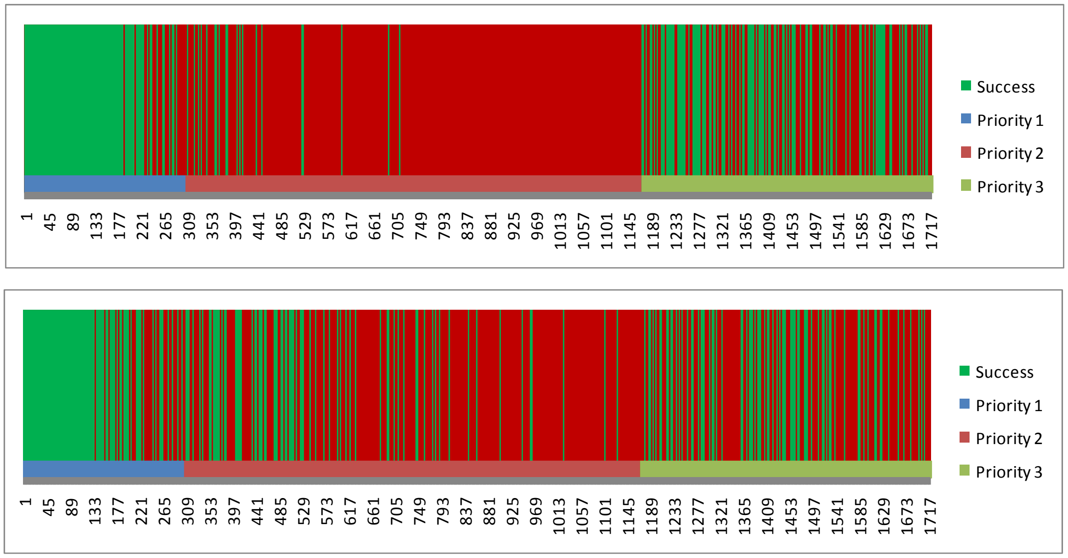

Figure 25. Results of Greedy Heuristic Approach For Two Ranked Lists.

When we perform the experiment with the Relay Coverage set to five and the needline limit to 32, the result approximates the number of links an EPLRS network is able to support, shown in Figure 26.

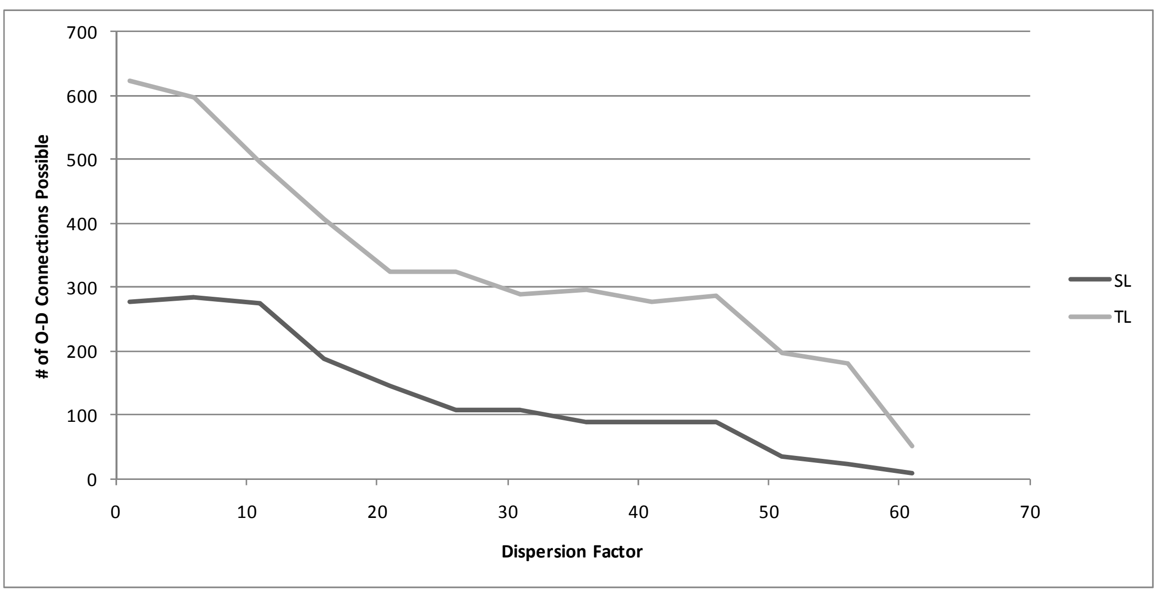

Figure 26. Number of Point-to-Point Connections, Restricted (Heterogeneous, 100W–5W).

We see the number of success of the TL BOI significantly decreased when we enforce the constraints (from ~1700 to ~600), due to the network's inability to satisfy the higher number of links. However, the TL BOI still provides more connections than the SL BOI at all dispersion factors.

When considered in a usage scenario where not all pairs are trying to communicate simultaneously, the presence of additional nodes that have the potential to act as relays increases the robustness of the network, making it less sensitive to changes in range between the origin and destination of duplex traffic and attacks that result in the loss of nodes.

4. Prioritized vs. Random

In the previous discussion, we assume a prioritization scheme for the traffic demands (described in Section III.F.4.). When this prioritization is removed, and the point-to-point attempts are between random pairs of nodes, we see how the addition of nodes in the TL BOI can affect the performance of high priority (Priority 1) traffic. Examining the number of connections possible at a particular dispersion factor for both a prioritized list and a random list, we see a decrease in successful connections for Priority 1, as shown in Figure 27.

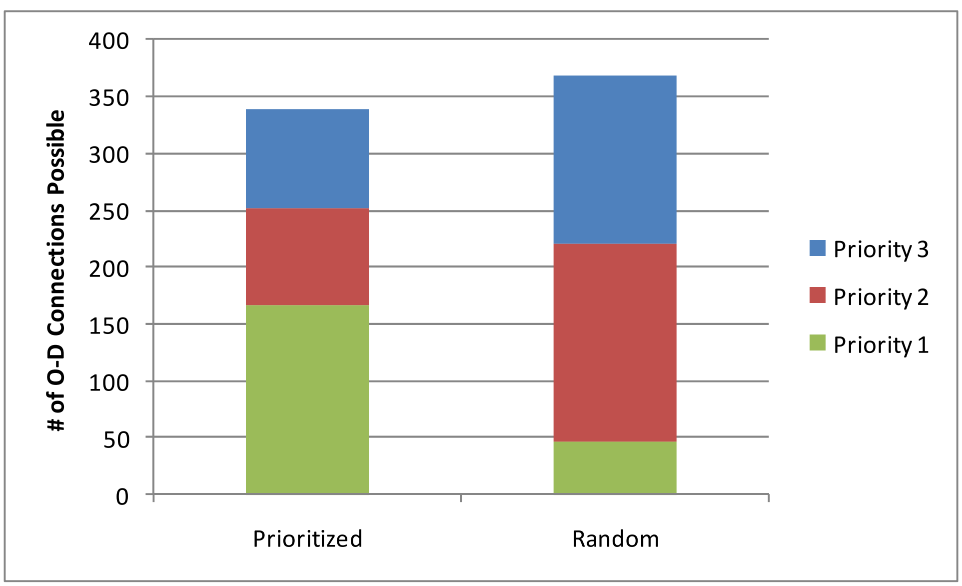

Figure 27. Effect of Randomizing Traffic Demand (Dispersion Factor = 25).

This is a result of the lower priority traffic "crowding out" the higher priority pairs. This trend is observable across a range of dispersion factors, shown in Figures 28 and 29.

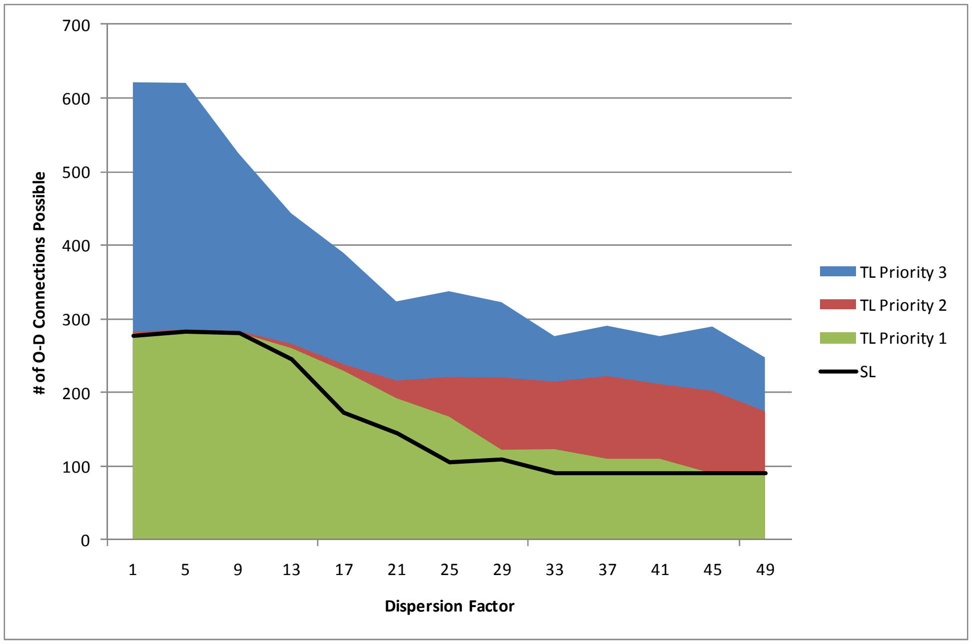

Figure 28. Number of Connections by Priority Group for Prioritized Traffic.

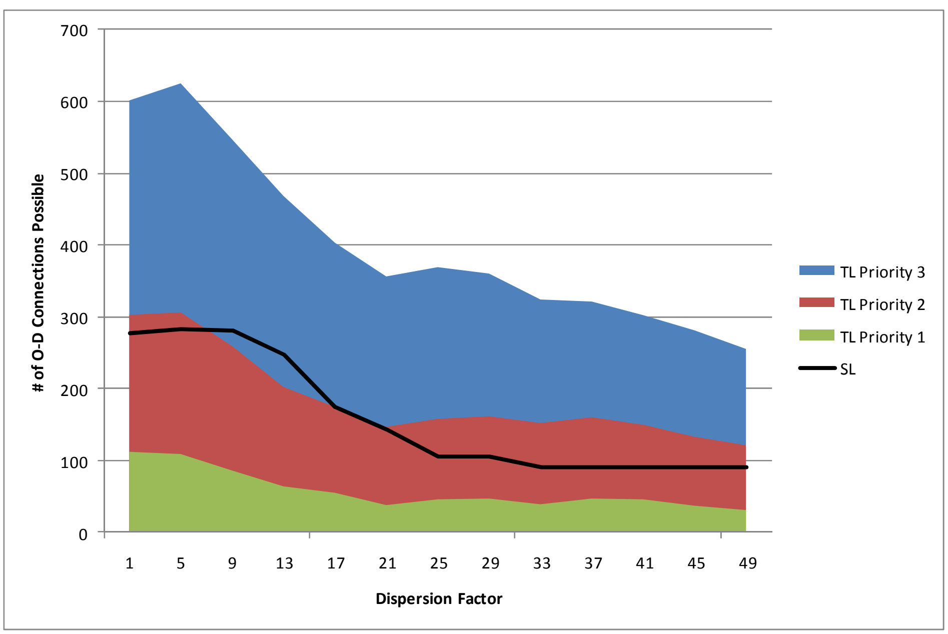

Figure 29. Number of Connections by Priority Group for Random Traffic.

In Figures 28 and 29, we show the number of connections possible for each priority group across a range of dispersion factors. The SL line represents the number of connections possible for the SL BOI, where we consider all connections Priority 1. Figure 28 shows that the TL BOI results in a greater number of Priority 1 connections being possible due to the ability of lower priority nodes serving as relays on Priority 1 links.

This crowding effect represents a possible degradation in network performance that could result from the increase in number of nodes. However, this effect can be mitigated through the establishment of good usage discipline and effective network management.

C. POSITION UPDATE MESSAGE MODEL

The position-update message model measures the likelihood of a successful transmission within the CSMA-CA multiple access scheme. A transmission attempt is a success if the circuit is idle when the attempt is made. Depending on the interval of message attempts, increasing the number of nodes leads to a saturation condition, where the further addition of nodes significantly decreases the likelihood of successful delivery.

Based on the EPLRS position filters, shown Table 8, we assume a nominal value of 30 sec for the transmission interval. We assume that each time step in the simulation is long enough to allow the full relay distance to be traversed, we conservatively assume each time step corresponds to 20 msec of real time. Converting the 30 sec interval into the corresponding number of time steps results in a transmission attempt every 1500 time steps.

We evaluate CSMA network performance for varying numbers of nodes, shown in Figure 30.

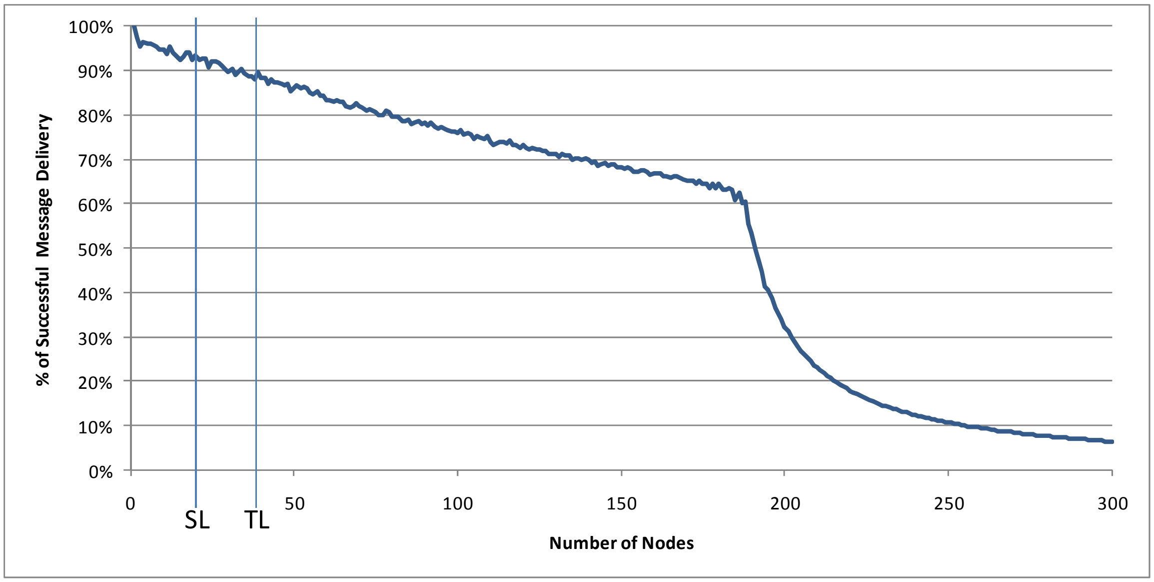

Figure 30. Percent of Successful Position-Update Message Delivery (30-sec interval). At this interval, both BOI are well below saturation.

The results of the simulation highlight the decrease in the percentage of successful message deliveries. The sudden drop at approximately 190 nodes corresponds to the saturation point of the network.

The bases of issue under consideration deal with the deployment of 18 and 42 RSs for the SL and TL BOI, respectively. Assuming a 30-sec interval between position messages, the increased number of nodes does not significantly affect the success rate for the bases of issue under consideration. If the interval is decreased to 5 sec, we see that the network becomes saturated at a much lower number of nodes, shown in Figure 31.

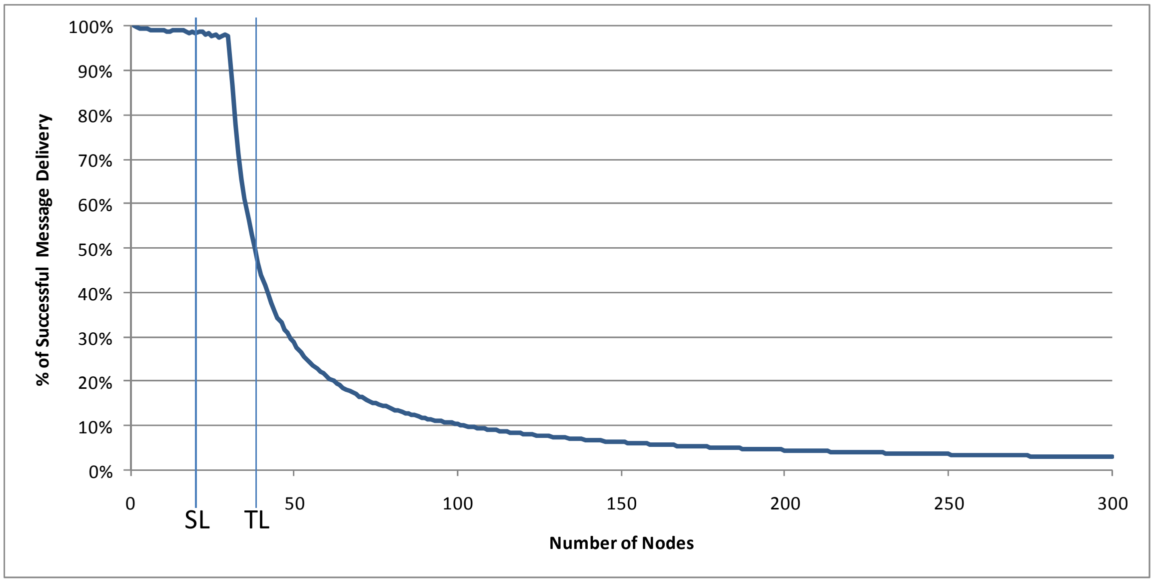

Figure 31. Percent of Successful Position Update Message Delivery (5-sec interval). At this interval, the TL BOI is above saturation.

It is important to keep in mind that this scenario refers to users on a single CSMA needline. If a future deployment scenario considered the fielding of a significantly greater number of RSs, the saturation effect could be mitigated by increasing the intervals between transmission attempts or establishing sub-networks to reduce the potential for collisions.

V. CONCLUSIONS AND RECOMMENDATIONS

We conclude this study by summarizing our results and proposing several ideas for future research on this topic.

A. RECOMMENDATION OF A BASIS OF ISSUE

In this thesis, we evaluate network performance using several different metrics under a variety of employment scenarios. We employ a physics-based approach to modeling wireless network behavior while maintaining applicability to EPLRS by accounting for its particular system characteristics. The goal is to represent EPLRS operation realistically enough to inform the decision regarding which BOI is best able to support the needs of the Army.

Based on the analysis of the three models presented, it is our finding that the deployment of additional radios to the Team Leaders need not have a significant detrimental effect on the performance of an EPLRS network. Furthermore, having more radios can improve the communications capabilities within a company under certain dispersion conditions. Total network throughput is higher, more point-to-point connections are possible, and overall situational awareness is improved through the use of position-update messages.

Effective network management is a primary factor in determining network performance given an increase in node density. As discussed in Sections IV.B.4. and IV.C., poor network planning and undisciplined use can result in degraded performance for both duplex needline supportability and position-update message delivery. In the duplex case, the absence of prioritization results in some needlines getting crowded out, reducing the ability to establish high-priority links. This effect can be mitigated by the development of usage policies that favor high-priority traffic. For position-update messages, overly frequent transmissions can negatively affect the position reporting functionality of a large network. This can be mitigated through the appropriate selection of position-update message intervals for the size of the network.

The focus of this thesis is on comparing network performance in the bases of issue under consideration. Factors such as cost, training, weight, power requirements, and system availability are not explicitly considered in this study, but are important in the final BOI determination. Based solely on the network performance factors considered here, we find no reason to reject the TL BOI.

B. PROPOSALS FOR FUTURE STUDIES

1. Account for Terrain Effects in TIREM

Future studies could take advantage of the capabilities of TIREM to evaluate network performance for a specific geographic area by evaluating received signal strength over a terrain profile. This would provide an accurate representation of how the network functions in various terrain situations.

2. Validate Model With Real-World Data

The results of this study could be evaluated for accuracy through the collection of real-world received signal strength and system usage data for deployed EPLRS networks. This would provide not only validation for the existing models, but could also inform the development of a demand model that more accurately represents real-world system employment.

3. Consider Point-to-Point Demands Over Time

Our model of point-to-point communications relies on a greedy heuristic to determine needline supportability within the network. A more dynamic approach would use a queuing model to represent the arrival and duration of duplex needline requests. Combined with a more accurate demand model, this would greatly improve understanding of needline requirements and system supportability.

4. Develop a More Realistic Position-Update Message Model

A more accurate model would account for the fact that position-update information is constantly changing and would implement a “time to live” for each message vice attempting to send the same message until it succeeds. In addition, this

thesis considers each blocked transmission attempt as a failure. An alternative approach would be to consider each completed message as a success regardless of how many times it had been blocked. Finally, the results of this model could be mapped to an actual performance metric, such as mean squared error, in estimating node position.

5. Examine Various Dispersion Scenarios

This study implements a particular dispersion model to describe node positions. Use of alternative models could improve the validity of the model results for specific deployments. For example, a more realistic scenario could constrain node locations to an existing road network, resulting in very different network topologies.

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